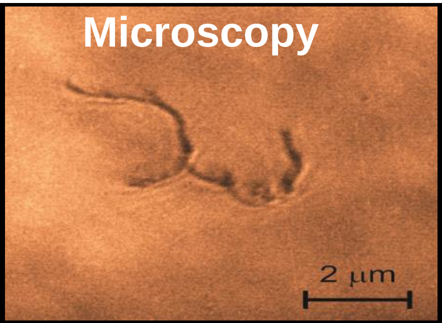
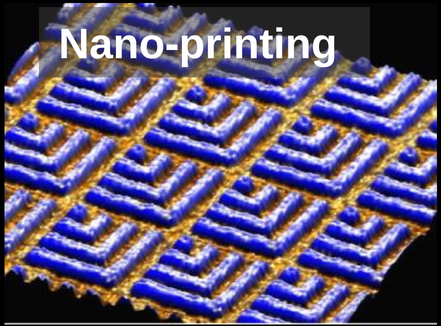
Compact, bright , Plasma-based EUV Lasers for Metrology

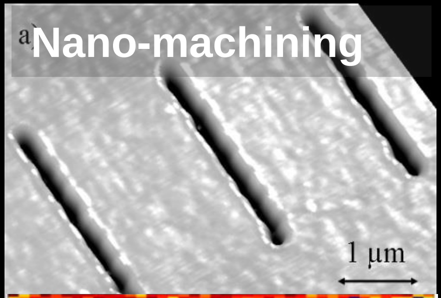
Jorge J. Rocca, B. Reagan, Y. Wang, D. Alessi, B. Luther, K. Wernsing, L. Yin, M. Curtis, M. Berrill, D. Martz, V. Shlyaptsev, S. Wang, F. Furch, M. Woolstron, D. Patel, M.C. Marconi, C.S. Menoni

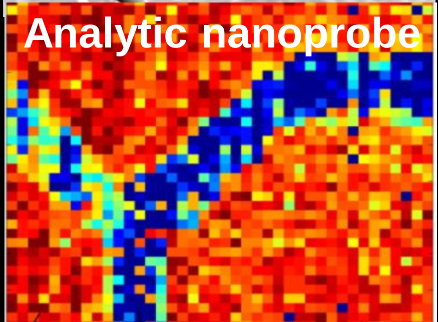
Engineering Research Center for Extreme Ultraviolet Science & Technology
Colorado State University

Work Supported by the NSF Engineering Research Centers Program and the US Department of Energy



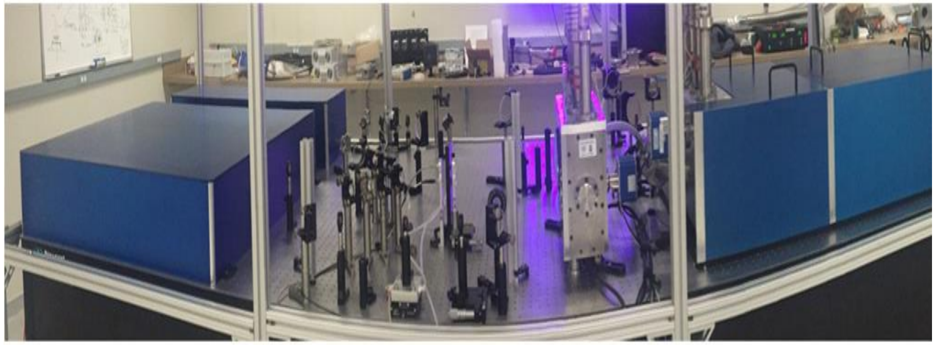


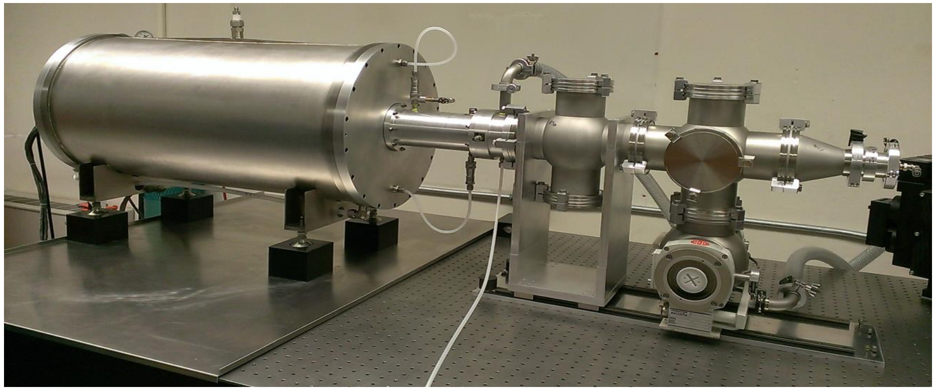




Applications require EUV laser pulses with pulse high energy (large number of photons), high average power

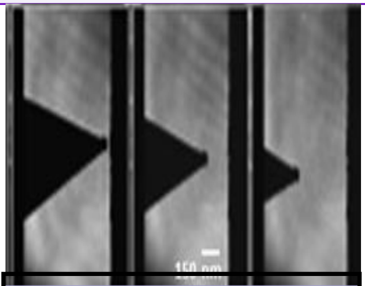
Compact atomic soft x-ray lasers



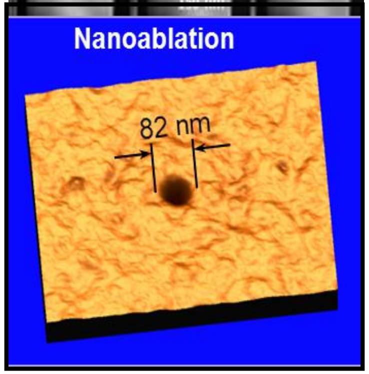


- **High pulse energy (μJ-mJ)**
- **High monochromaticity ($\lambda/\Delta\lambda < 10^{-4}$)**
- **High peak spectral brightness**

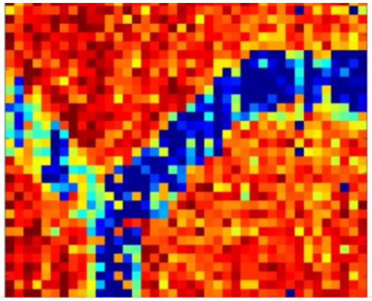
Single shot imaging



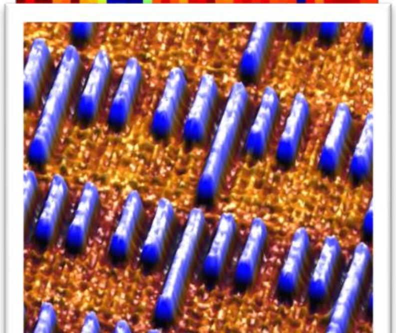
Nanoscale ablation



Analytic nanoprobes

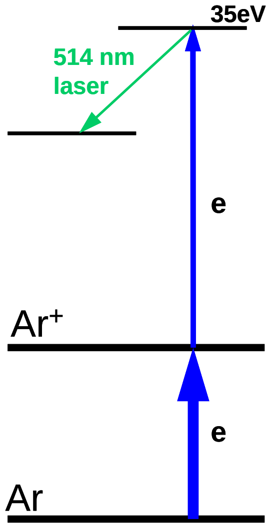


Error-free nanopatterning

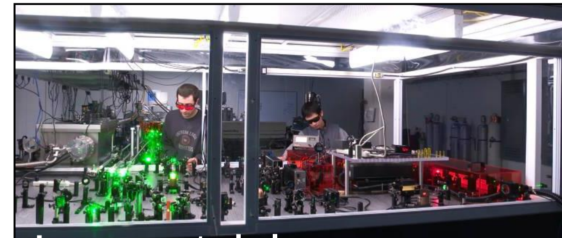


EUV lasers can be created by electron impact excitation of highly ionized atoms in dense plasmas

Singly ionized Ar ion, Kr ion lasers in the visible spectral region



Highly ionized (8-35 times) in the EUV/SXR spectral region


Laser created plasma

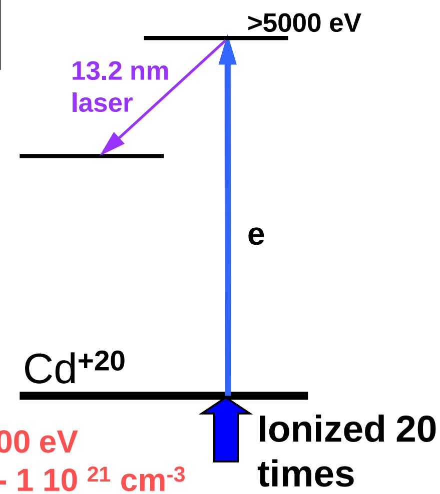

Discharge created plasma

$$h\nu = \Delta E \propto Z^{2.5}$$

Plasma requirements:
$T_e \sim 5$ eV
$N_e \sim 1\ 10^{14}$ cm^{-3}

NexTe increases by 10^7-10^{10}

$T_e \sim 100$- 1000 eV
$N_e \sim 1\ 10^{19}$ - $1\ 10^{21}$ cm^{-3}



Advantage of λ= 47 nm for defect inspection

Assessing the wavelength extensibility of optical patterned defect inspection

Bryan M. Barnes*, Hui Zhou, Mark-Alexander Henn, Martin Y. Sohn, and Richard M. Silver Engineering Physics Division, National Institute of Standards and Technology,
100 Bureau Drive MS 8212, Gaithersburg, MD, USA 20899-8212

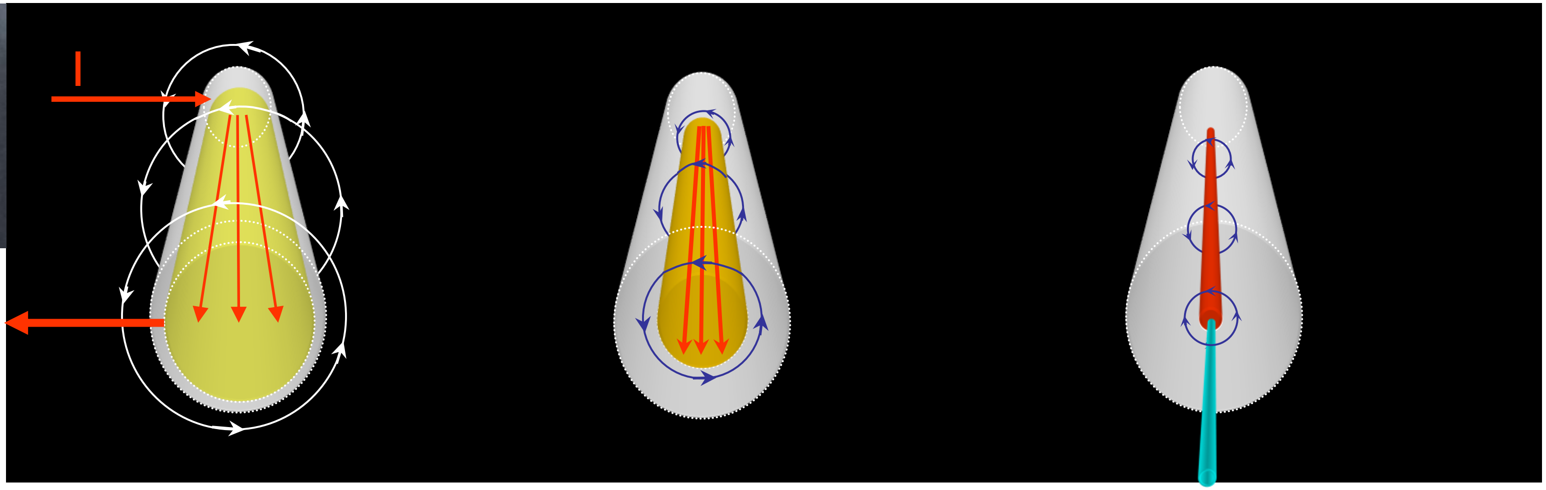
ABSTRACT

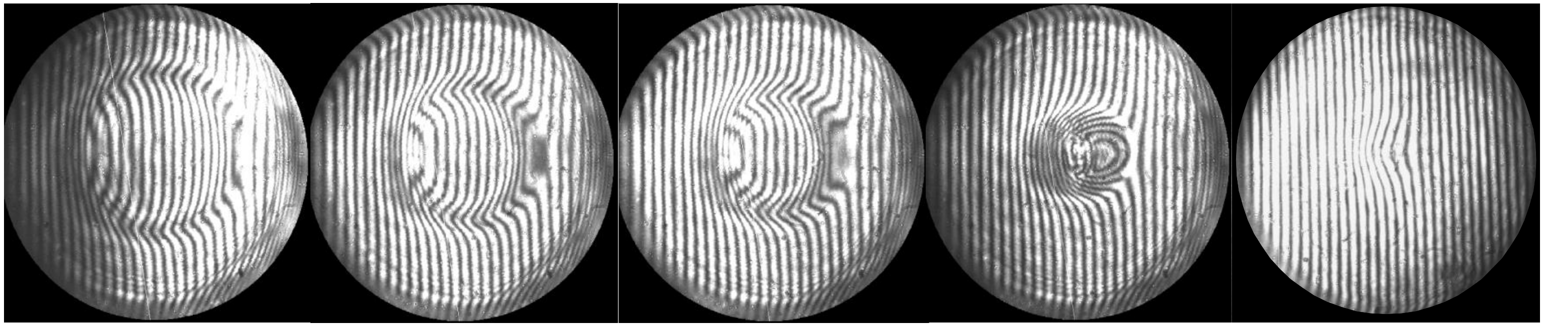
Qualitative comparisons have been made in the literature between the scattering off deep-subwavelength-sized defects and the scattering off spheres in free space to illustrate the challenges of optical defect inspection with decreasing patterning sizes. The intensity scattered by such a sphere (for diameters sized well below the wavelength) is proportional to its diameter to the sixth power, but also scales inversely to the fourth power of the wavelength. This paper addresses through simulation the potential advantages of applying shorter wavelengths for improved patterned defect inspection. Rigorous finite-difference time-domain 3-D electromagnetic modeling of the scattering from patterned defect layouts has been performed at five wavelengths which span the deep ultraviolet (193 nm), the vacuum ultraviolet (157 nm and 122 nm), and the extreme ultraviolet (47 nm and 13 nm). These patterned structures and defects are based upon publicly disclosed geometrical cross-sectional information from recent manufacturing processes, which then have been scaled down to an 8 nm Si linewidth. Simulations are performed under an assumption that these wavelengths have the same source intensity, noise sources, and optical configuration, but wavelength-dependent optical constants are considered, thus yielding a more fundamental comparison of the potential gains from wavelength scaling. To make these results more practical, future work should include simulations with more process stacks and with more materials as well as the incorporation of available source strengths, known microscope configurations, and detector quantum efficiencies. In this study, **a 47 nm wavelength yielded enhancements in the signal-to-noise by a factor of five compared to longer wavelengths and in the differential intensities by as much as three orders-of-magnitude compared to 13 nm, the actinic wavelength for EUV semiconductor manufacturing.**

Metrology, Inspection, and Process Control for Microlithography XXXI, edited by Martha I. Sanchez, Vladimir A. Ukraintsev Proc. of SPIE Vol. 10145, 1014516 · © 2017 SPIE · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2262191

Soft x-ray laser amplification in discharge created plasmas: capillary discharge lasers

A fast current pulse compresses a plasma creating a hot and dense column with aspect ratio L/d > 1000





Sequence of on-axis interferograms showing rapid plasma column compression in an Ar capillary discharge

Demonstration of a discharge-pumped EUV laser: capillary discharge laser in Ne-like Ar

VOLUME 73, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1994

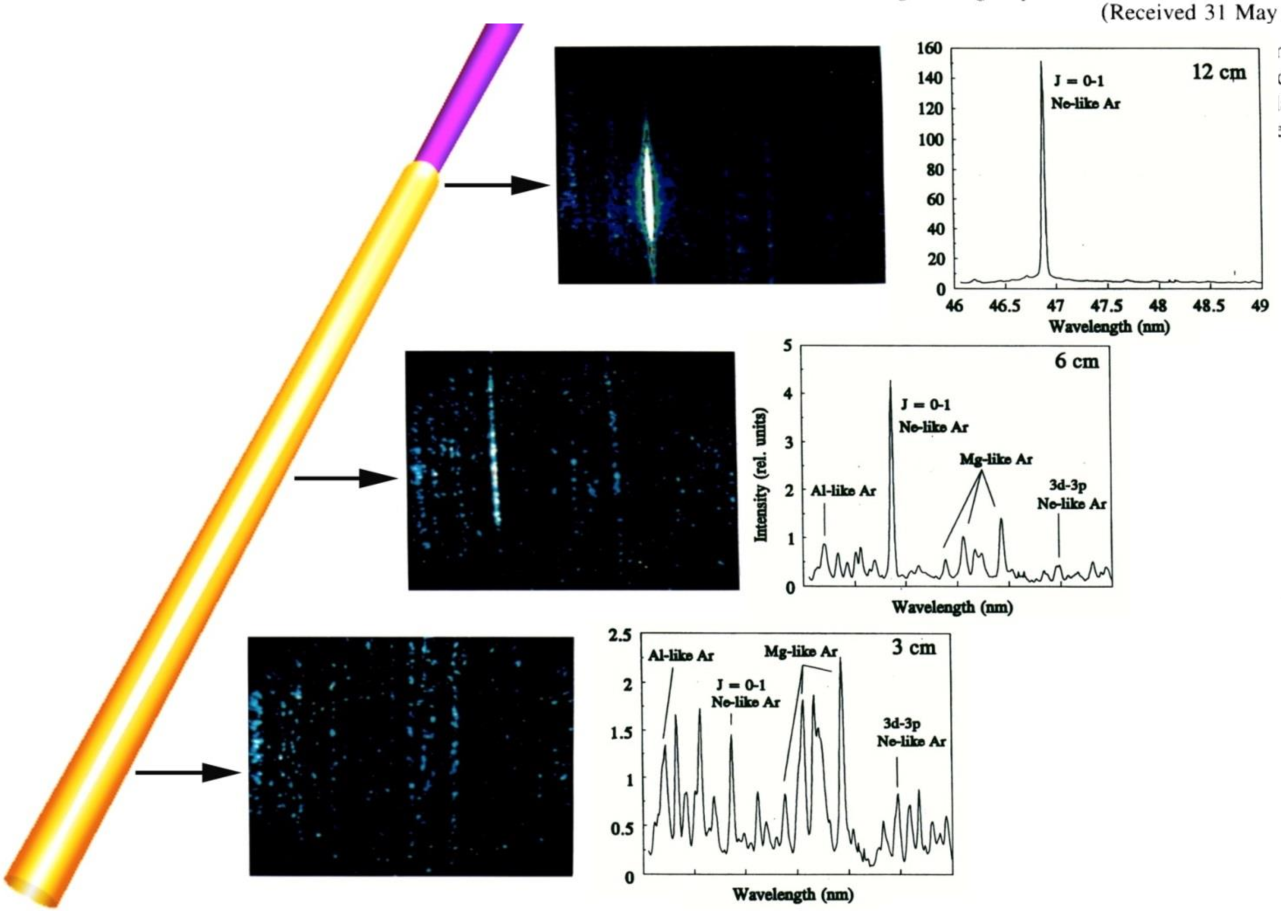
Demonstration of a Discharge Pumped Table-Top Soft-X-Ray Laser

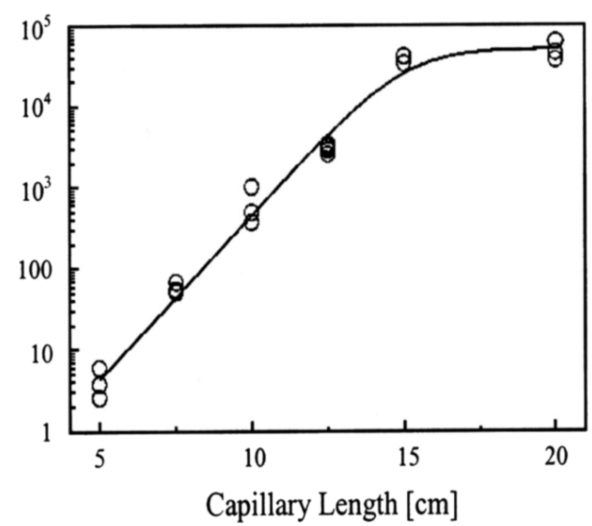
J. J. Rocca, V. Shlyaptsev,* F. G. Tomasel,† O. D. Cortázar,‡ D. Hartshorn, and J. L. A. Chilla

Electrical Engineering Department, Colorado State University, Fort Collins, Colorado 80523

(Received 31 May 1994)

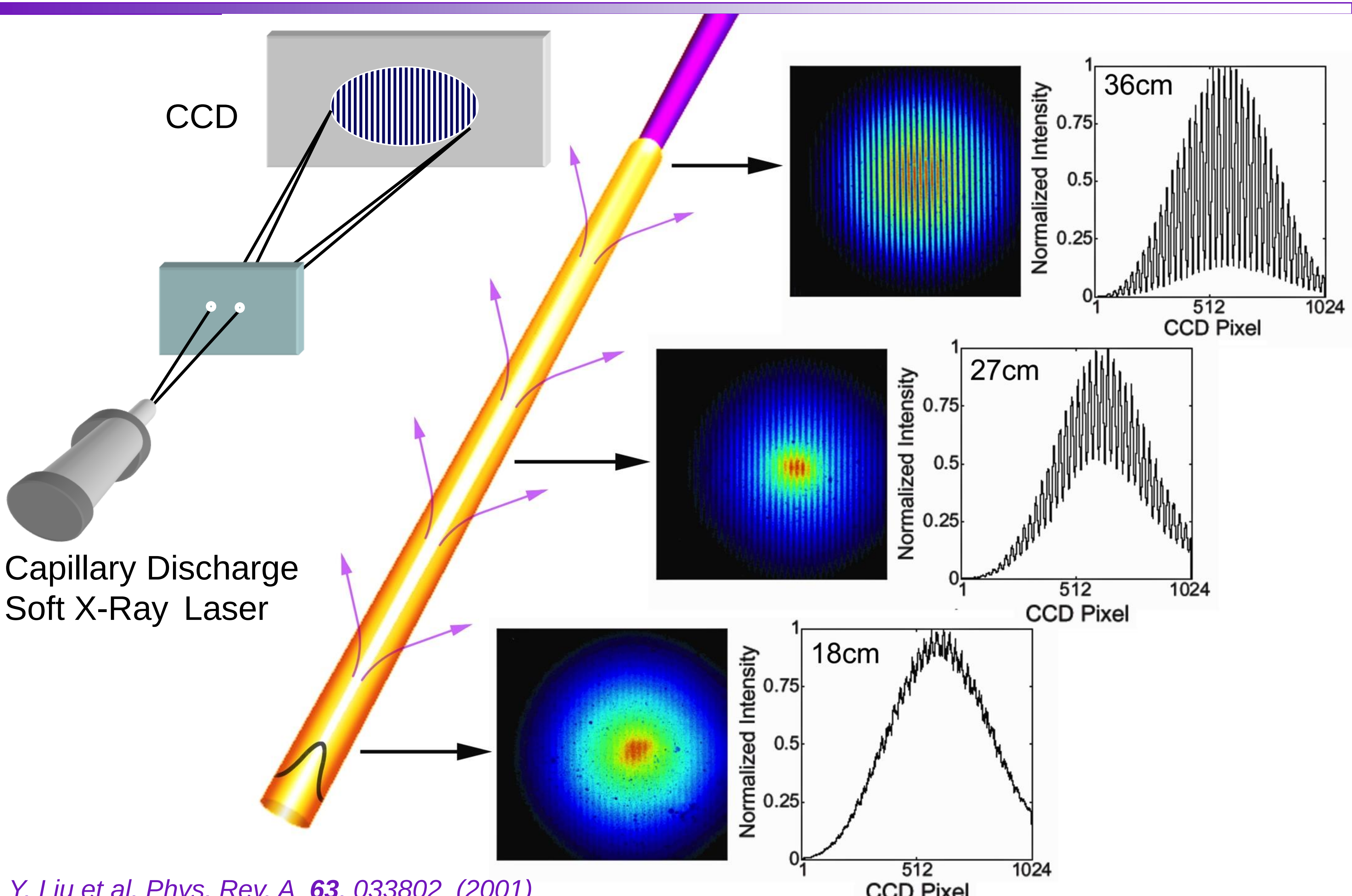
nplification (gl = 7.2) in a discharge-created
discharge was used to excite plasma columns
ation inversion in the J = 0-1 line of Ne-like
eam divergence was measured to be <9 mrad.





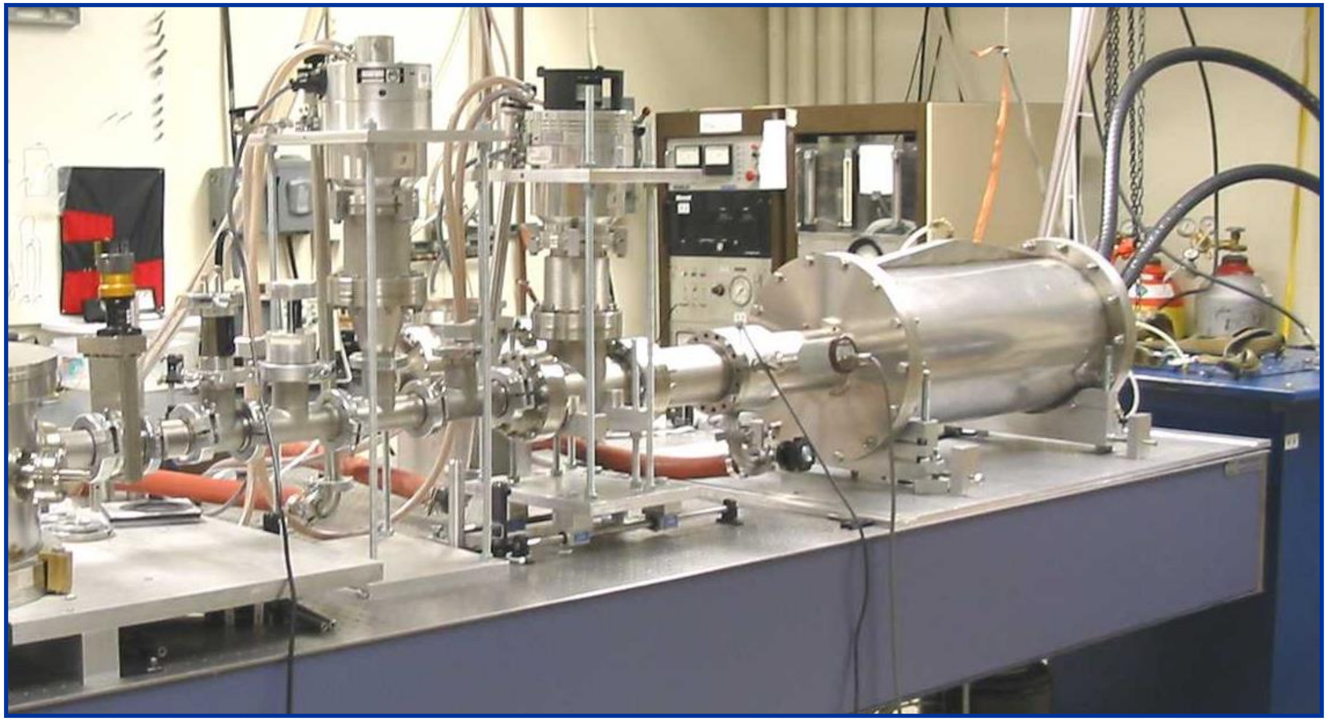
J.J. Rocca et al. Phys. Rev. Lett 73,(1994), Phys. Rev. Lett. 77, (1996)

Essentially full spatial coherence is achieved increasing the capillary length



Y. Liu et al. Phys. Rev. A ***63****, 033802 (2001)*

Table-top laser in Ne-like Ar produces coherent average power at λ=46.9 nm similar to synchrotron beam line



Ne-like Ar Capillary discharge 46.9 nm laser

High average power: up to 3 mW

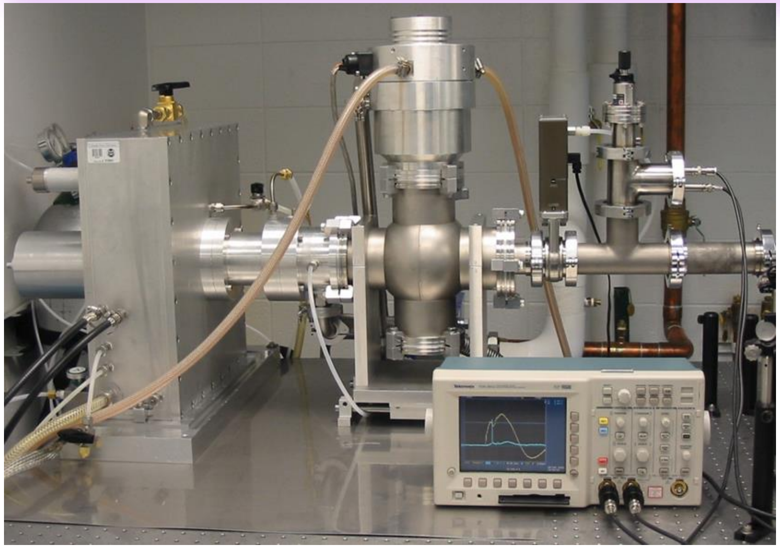
High pulse energy: 0.1 mJ - 0.8 mJ @4 Hz

Narrow spectral bandwidth: $\Delta\lambda/\lambda = 3 \times 10^{-5}$

Beam divergence: $\theta = 4.5$ mrad

B. Benware et al. Phys.Rev.Lett, 81, 5804, (1998) ; C. Macchietto Opt. Lett 24, 1115, (1999)

CSU Capillary Discharge Laser Technology is today turn-on key



2005

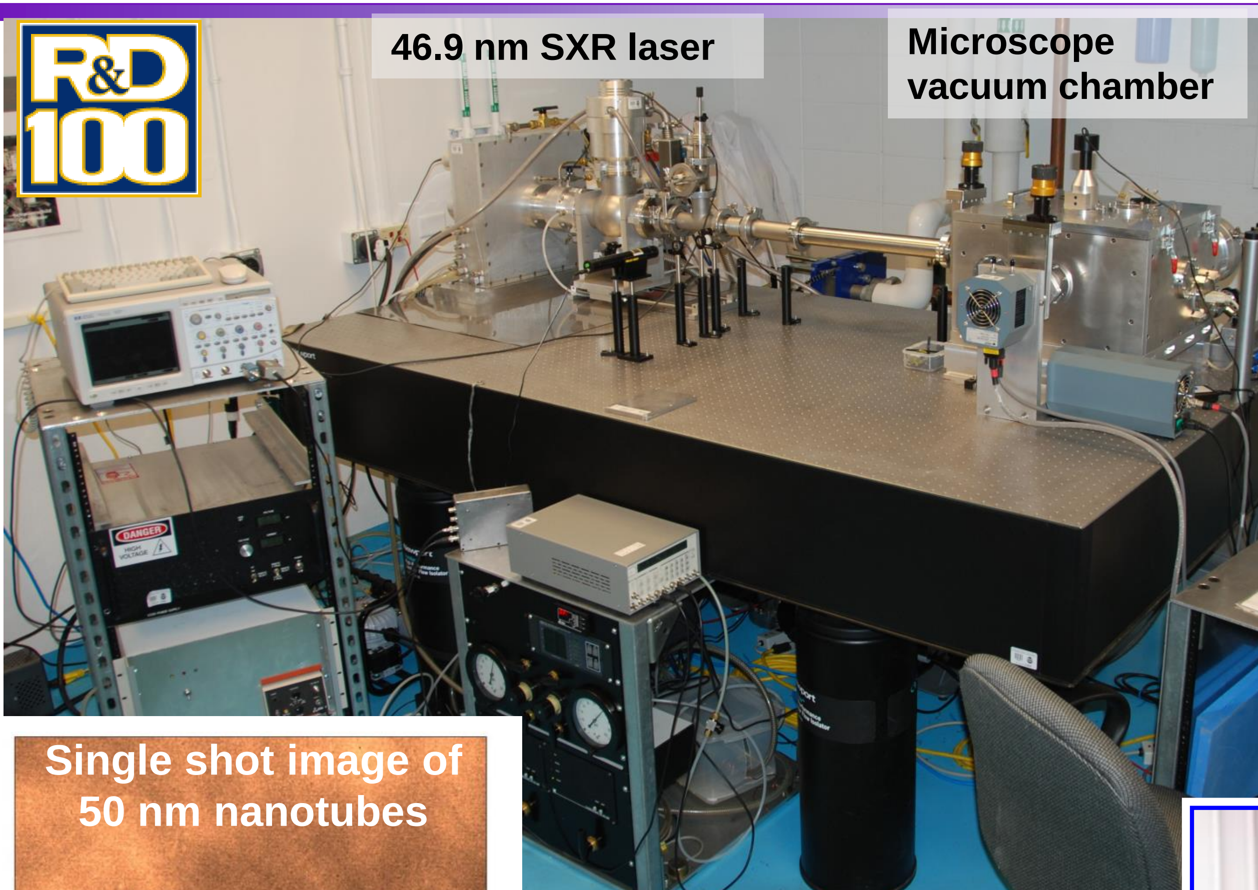
- 10 microjoule /pulse
- 0.15 mW average power
- 1-12 Hz repetition rate
- Pulse duration ~1.5 ns
- $\Delta\lambda/\lambda < 1 \times 10^{-4}$

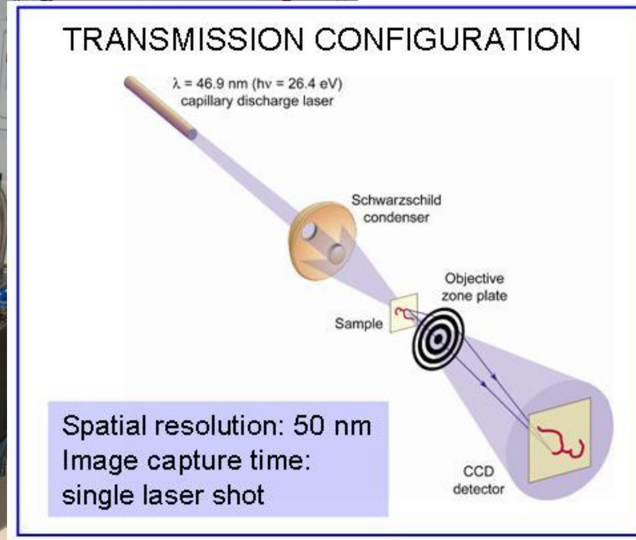
S. Heinbuch, M. Grisham, D. Martz, J.J. Rocca
Optics Express, 30,2095, (2005)

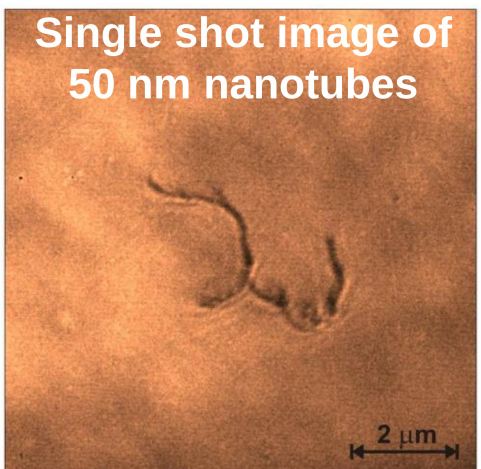
2015

- **50** microjoule /pulse
- 0.5 mW average power
- 1-10 Hz repetition rate
- Pulse duration ~1.5 ns
- $\Delta\lambda/\lambda < 1 \times 10^{-4}$
- Jitter < 2ns

Compact λ= 46.9 nm full field microscope





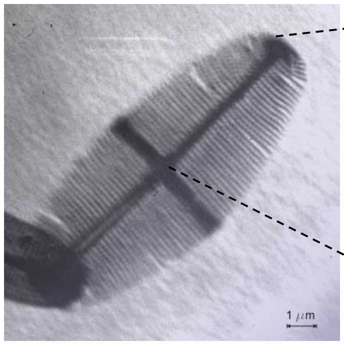


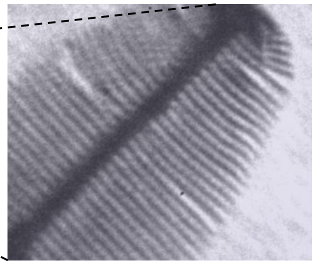
C. Brewer, et al, Opt. Lett. ***33***, *518 (2008)*

EUV microscopes captures images of nanostructures with very high resolution

TRANSMISSION
NA=0.32 (M~1000)

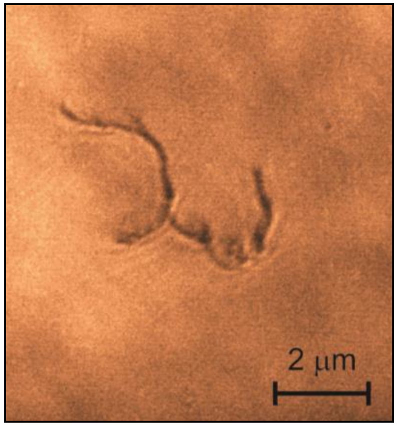
200 nm half period diatom





5 sec exposure

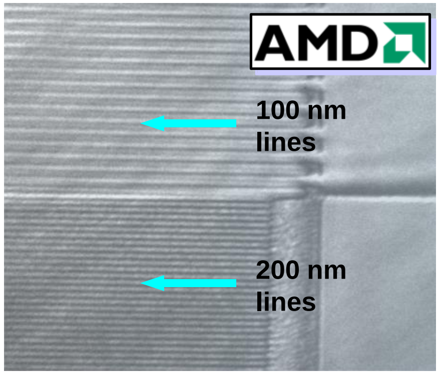
50 nm carbon nanotube



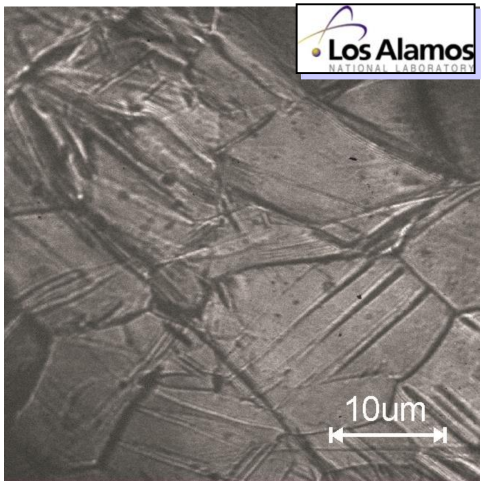
Single shot, 1.5 ns exposure

C. Brewer, et al, Opt. Lett. 33, 518 (2008)

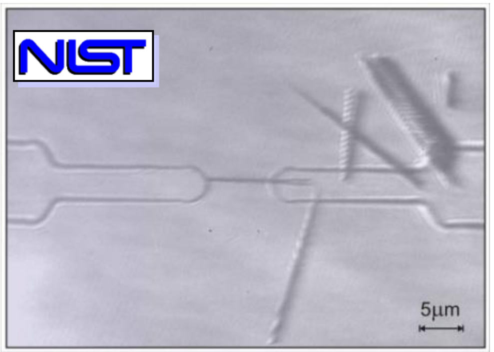
REFLECTION
NA=0.12 and 0.19 (M~250)
5-20 sec exposures



Partially Processed semiconductor chip



Zr surface showing twin in grain

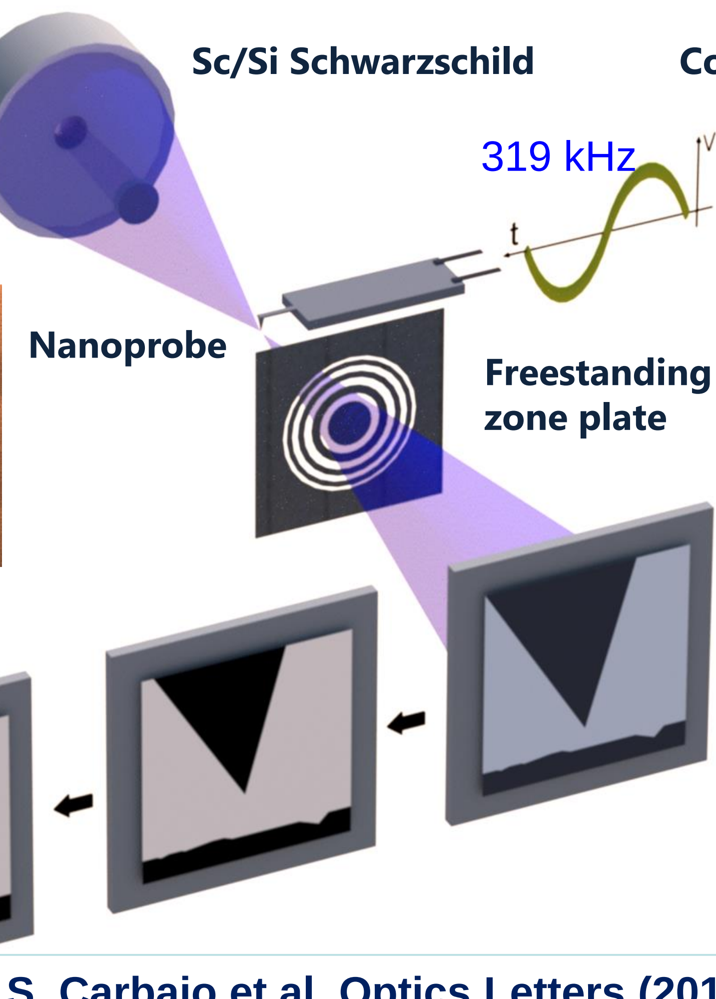


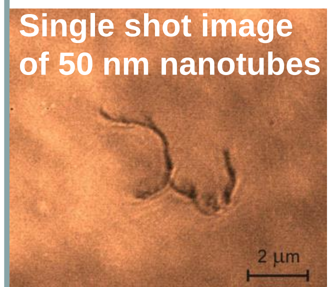
100 thick GaN nanowire between Al contacts

F. Brizuela et al, Opt. Express 13 :3983, (2005).

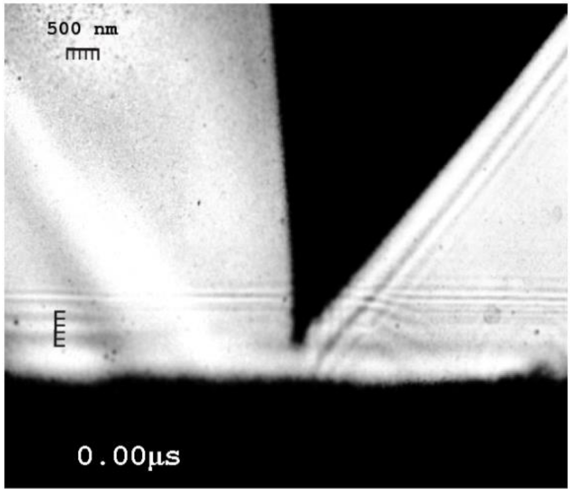
Movies of Nano-scale Dynamics on a Table-top

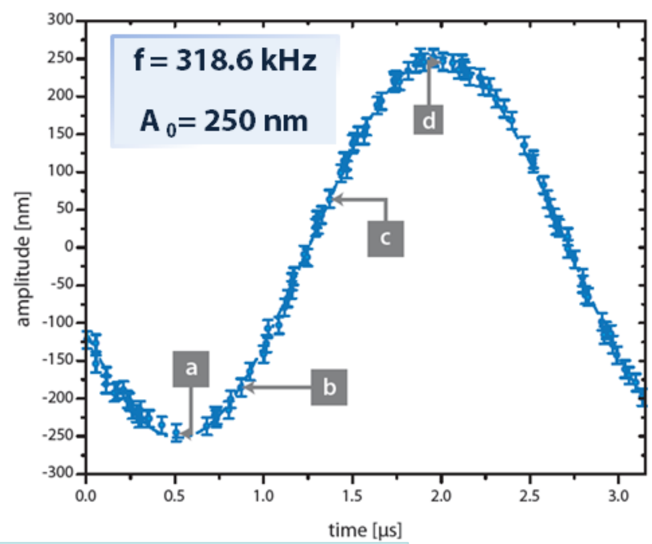
SXR laser





B. Brewer et al
Optics Lett.
33,518,(2008)

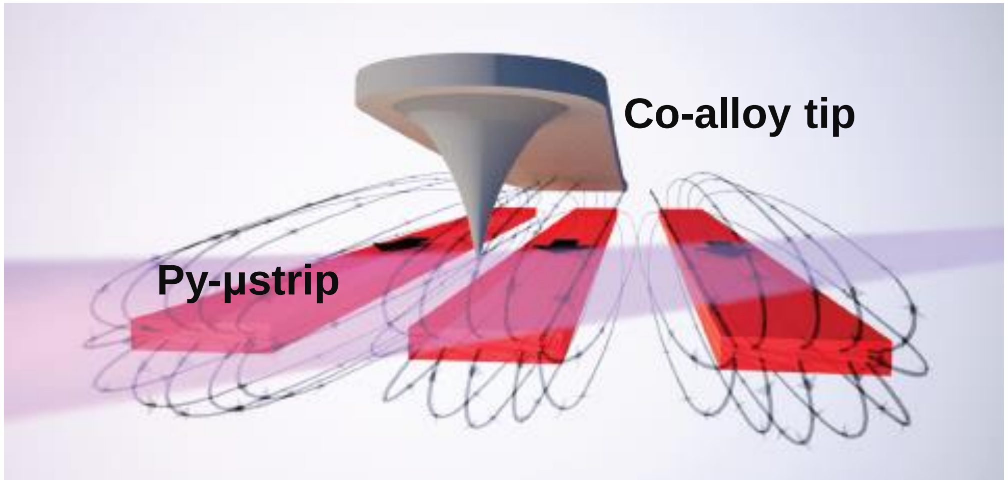


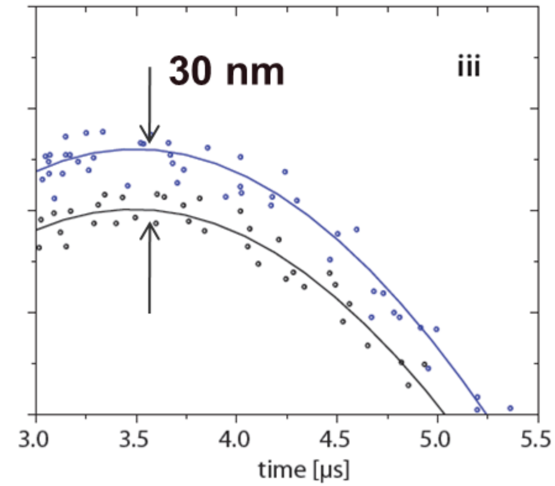


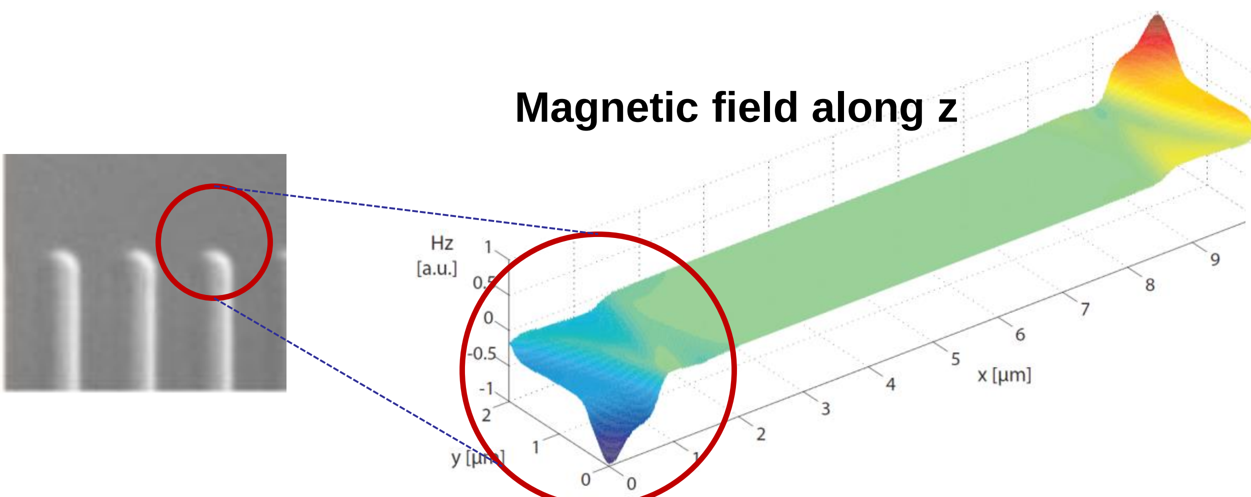
S. Carbajo et al. Optics Letters (2012)

Visualizing Nano-scale Dynamic Interactions

Magnetic force microscope tip interaction with stray magnetic field



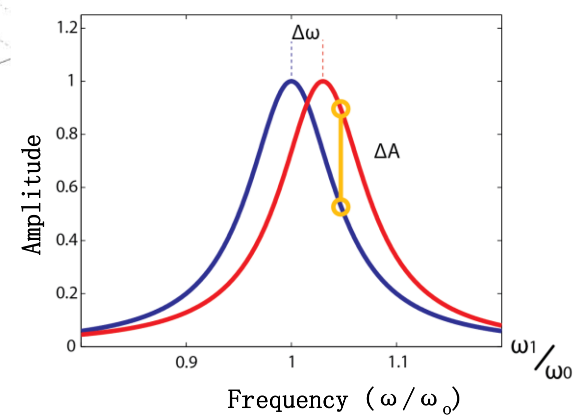




Effective Spring Constant

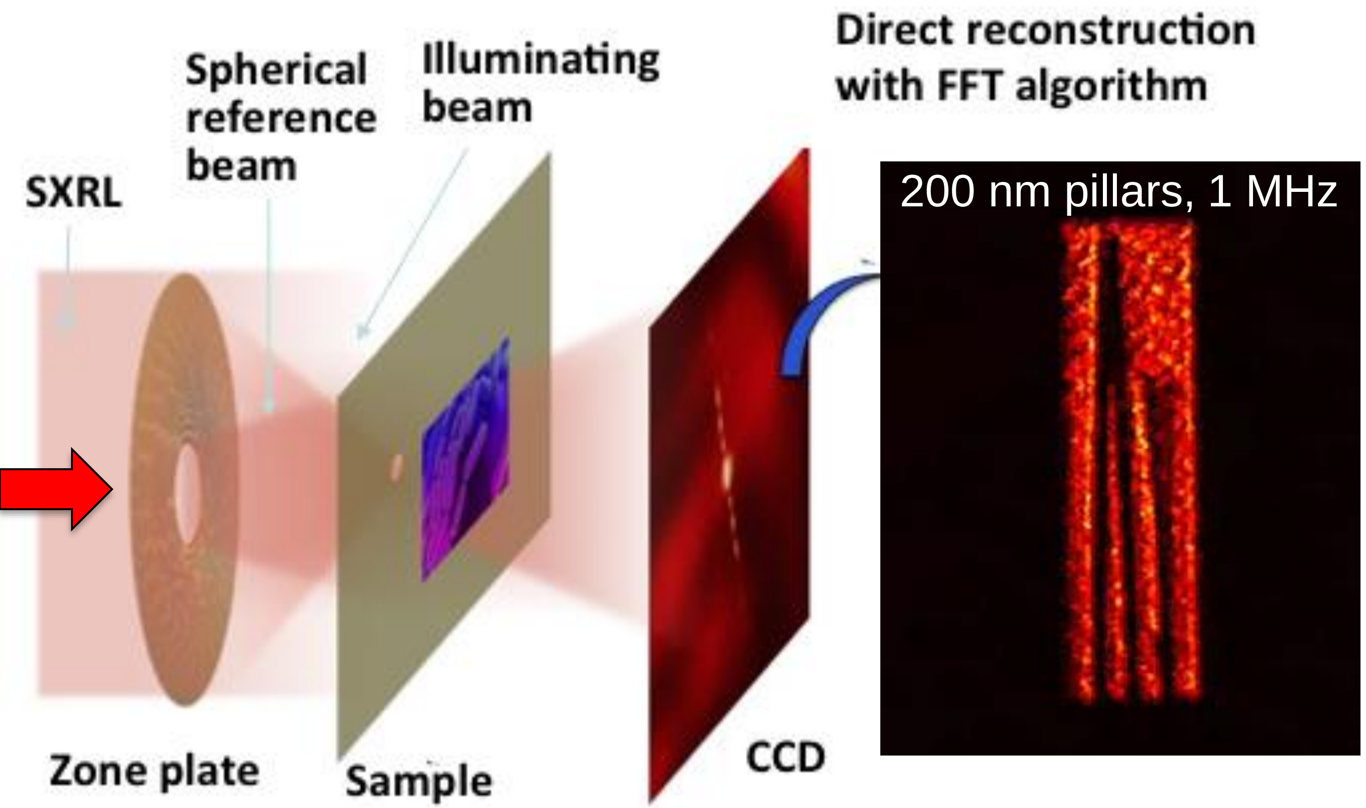
$k$tip + $k$force

$$\omega_{res}^2 = k/m = 1/m\,(k - \partial F/\partial z)$$

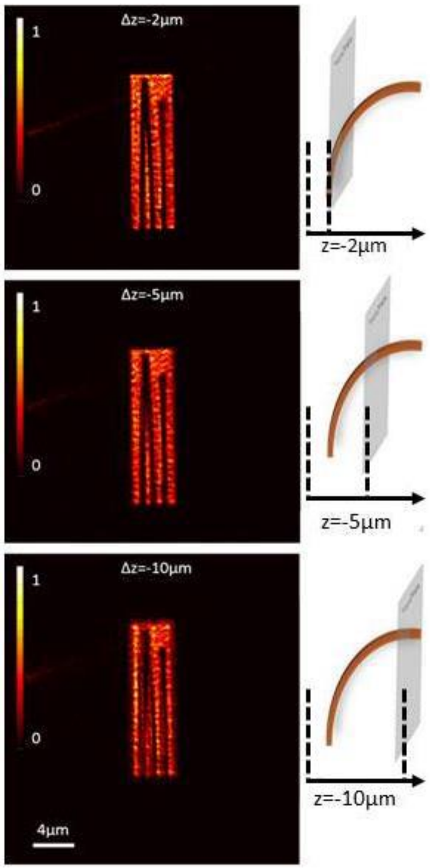


S. Carbajo et al. Optics Letters (2012)

Real time nano-scale resolution imaging by Fourier Holography



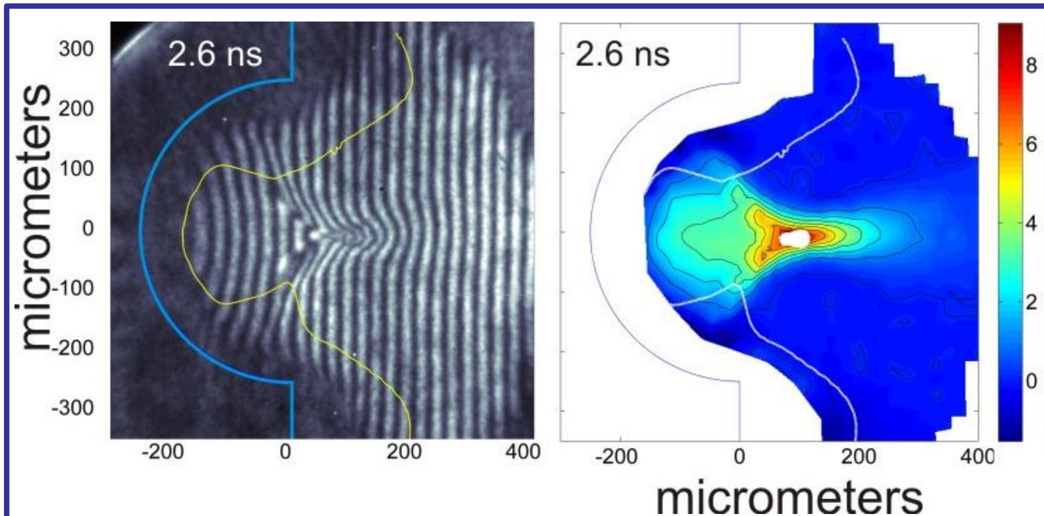
Numerical back-propagation

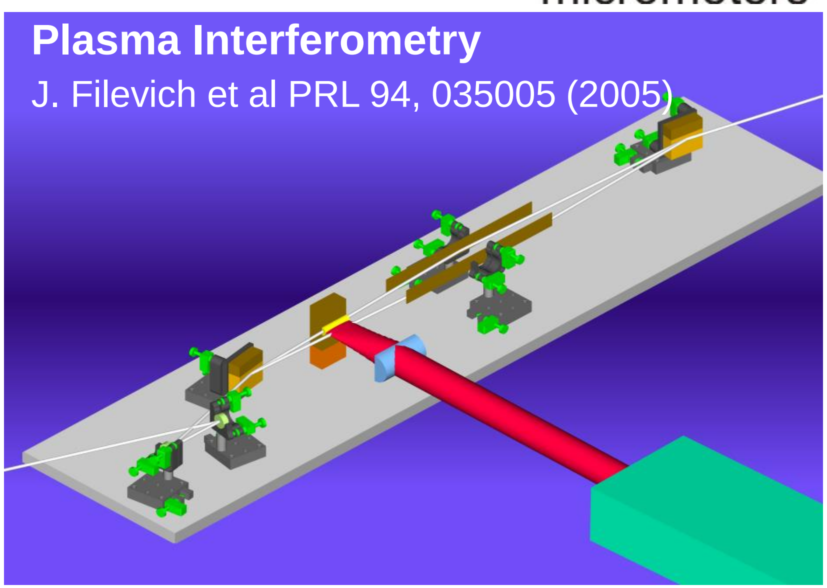


Measurements to validate a model that describes the nonlinear interaction between nanopillars

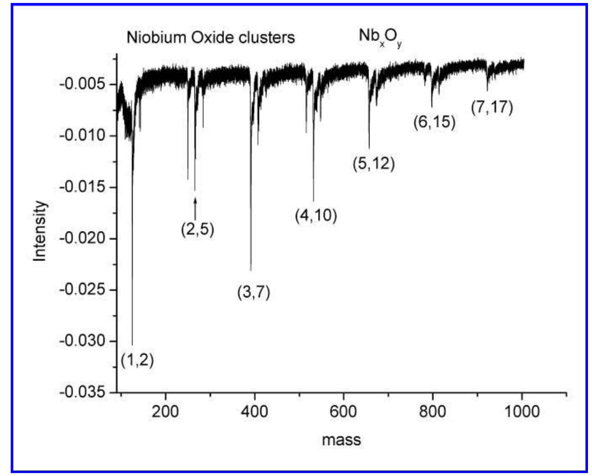
N. Monserud, M. Marconi et al. Optics Express , 22, 4161, (2014)

Applications in dense plasma diagnostics and photochemistry

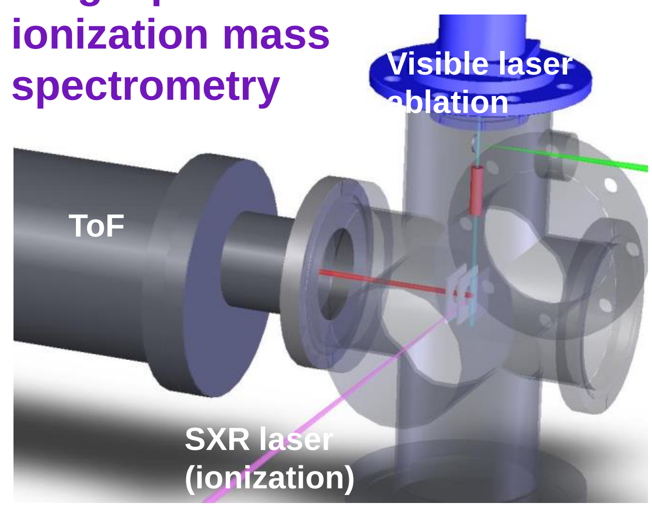




*M. Purvis et al. Phys. Rev.E, **76**, (2007); **124**, (2010)*



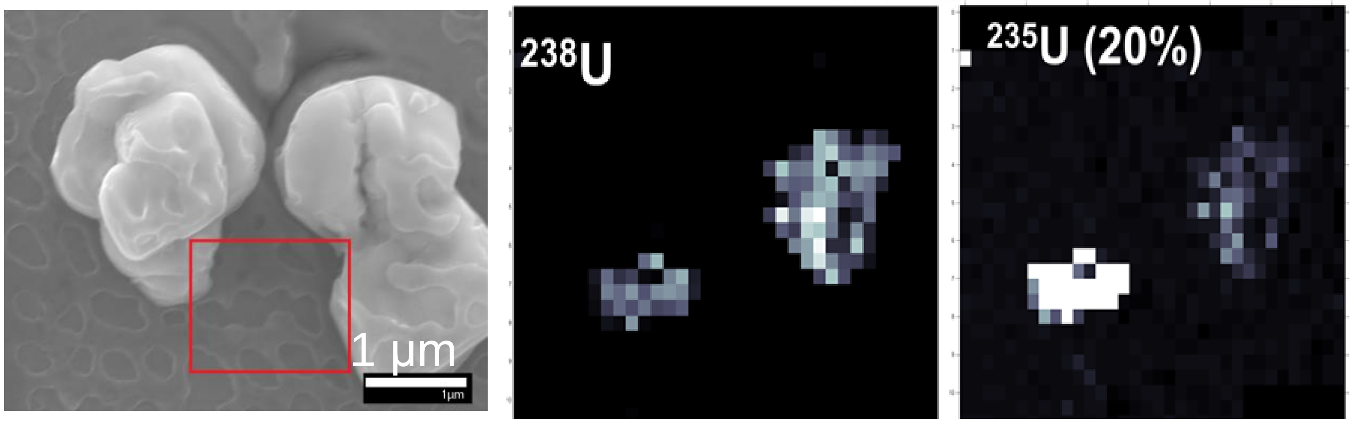
Single photon ionization mass spectrometry



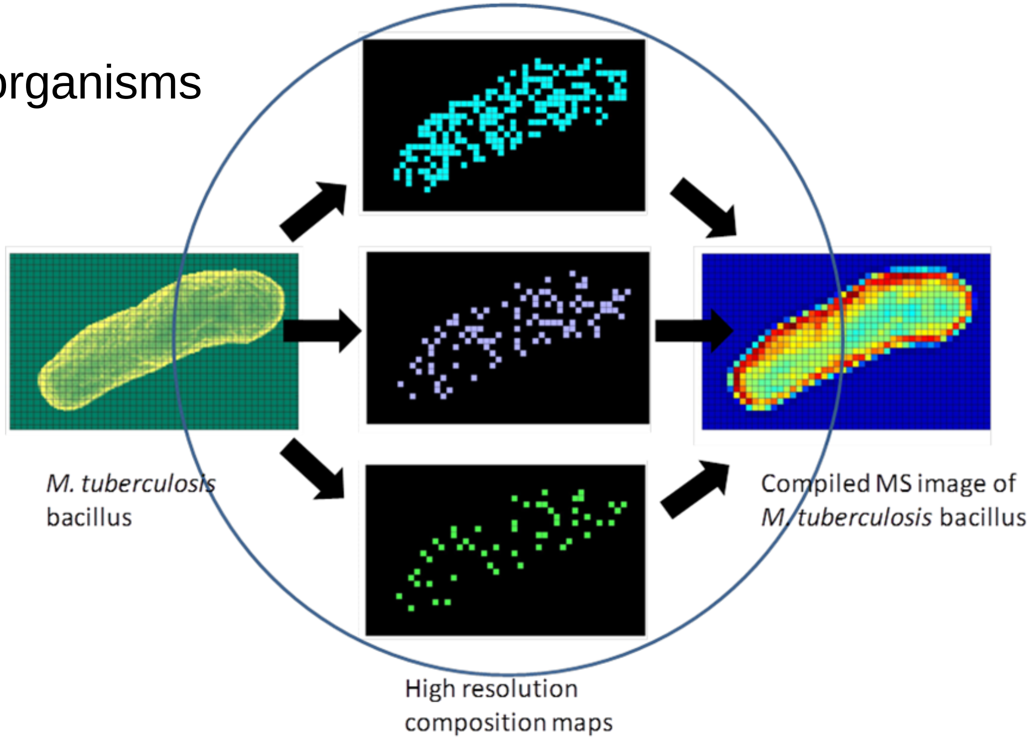
*F. Dong et al. J.Chem.Phys **124,** (2006)*
*F. Dong et al. J.Am.Chem Soc. **131**, (2009)*

Beyond morphology: composition

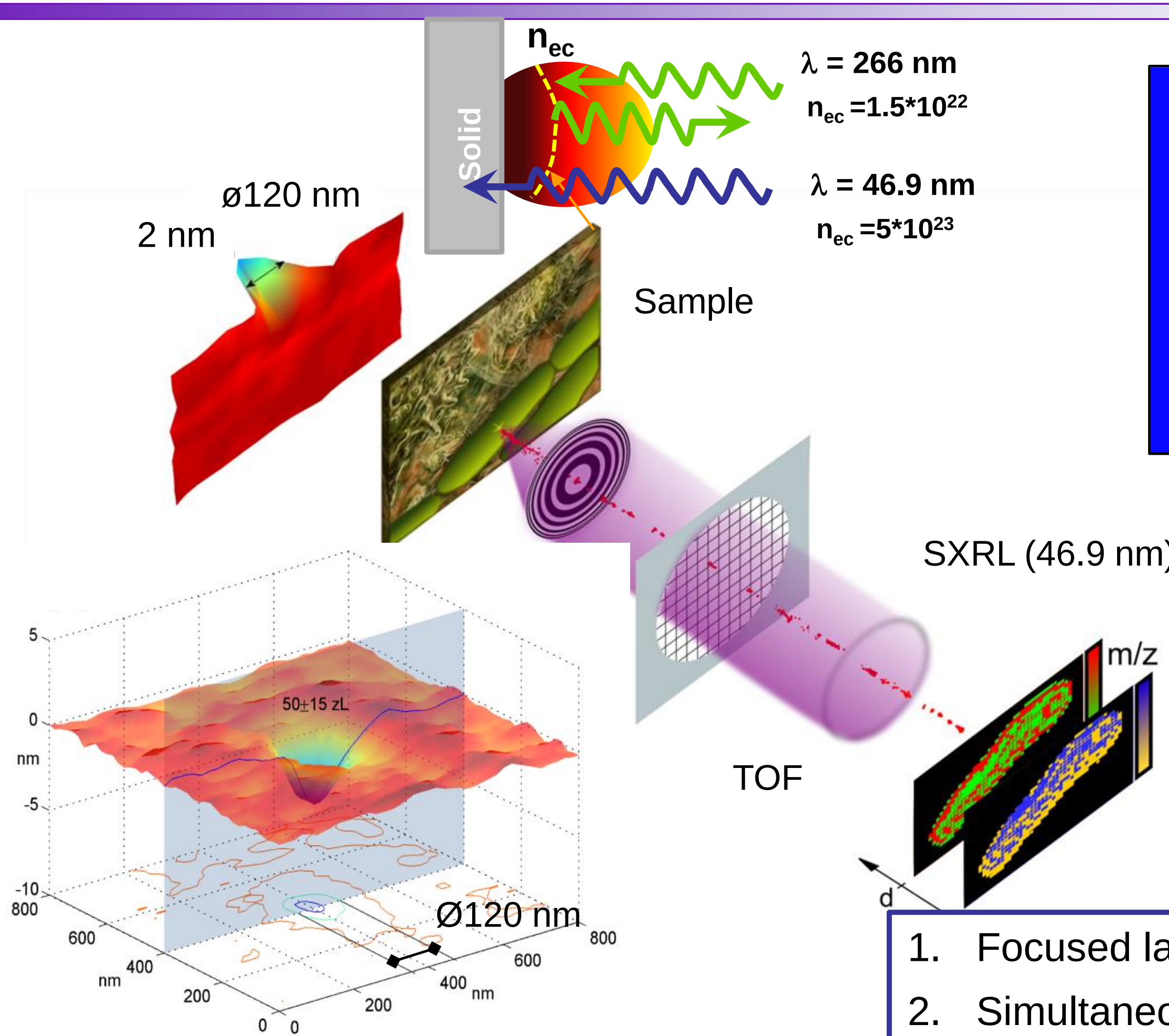
Condensed phase micro- and nanostructures

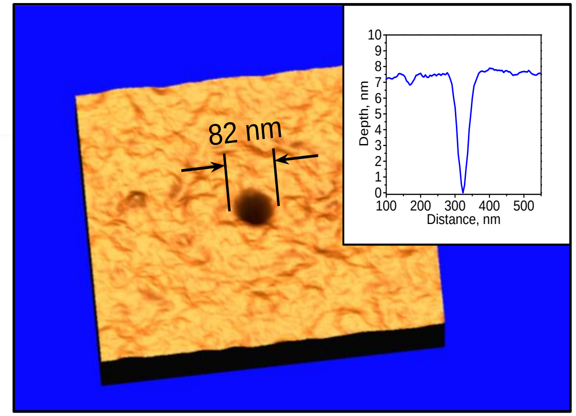


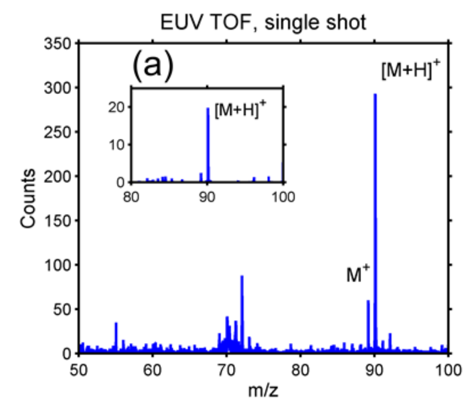
Micro-organisms



EUV laser ablation time-of-flight (TOF) imaging mass spectrometry

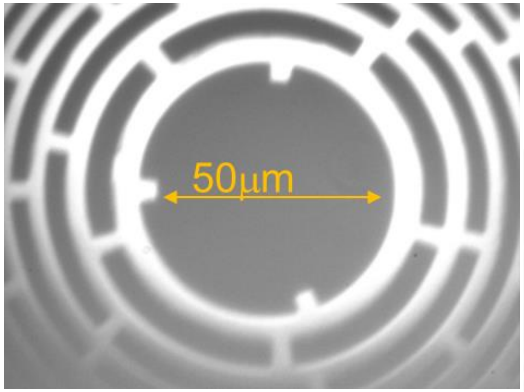




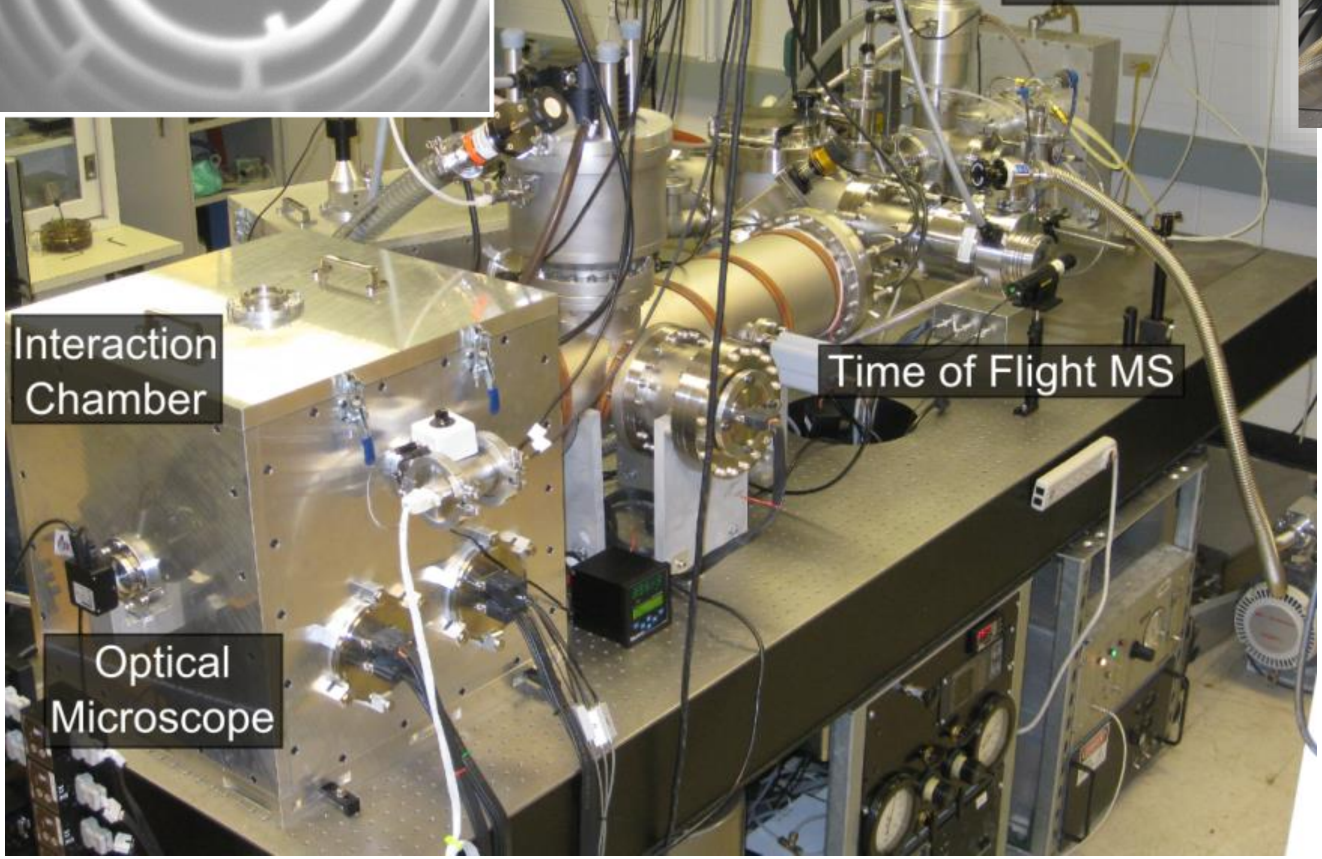


1. Focused laser ablates the material
2. Simultaneously ionizes species in the ablation plume
3. Ions are extracted into the mass spectrometer

3D imaging EUV mass spectrometry imaging nanoprobe



EUV Optics
Fresnel zone plate 0.16 NA



EUV laser

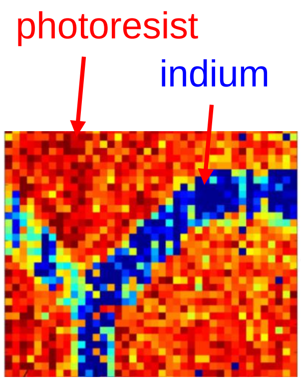
- **Wavelength: 46.9 nm**
- **Energy per pulse > 10 μJ**
- **Repetition rate: 12 Hz**
- **Pulse duration ~1.5 ns**

S. Heinbuch Optics Express vol. 13, 4050 (2005)

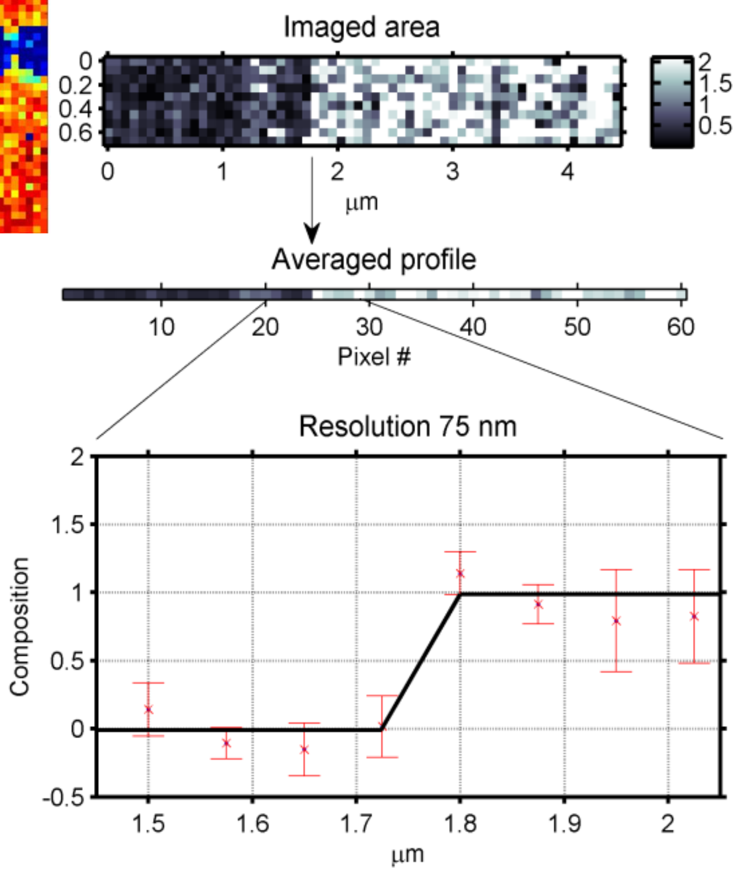
Optics engineered by W. Chao and E. Anderson at Center of X-Ray Optics, Lawrence Berkeley Lab.

E.H. Anderson, IEEE J. Quantum Electronics, vol.42, 27, 2006

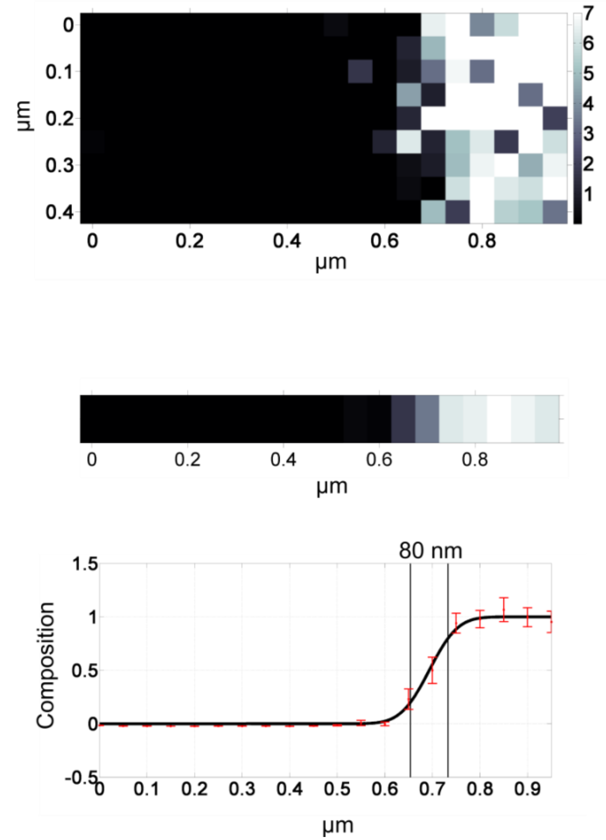
80 nm lateral resolution was measured on both inorganic and organic samples



Photoresist edge



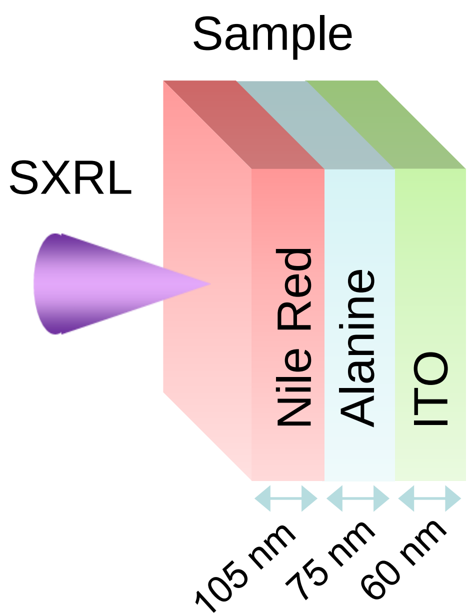
Nickel edge

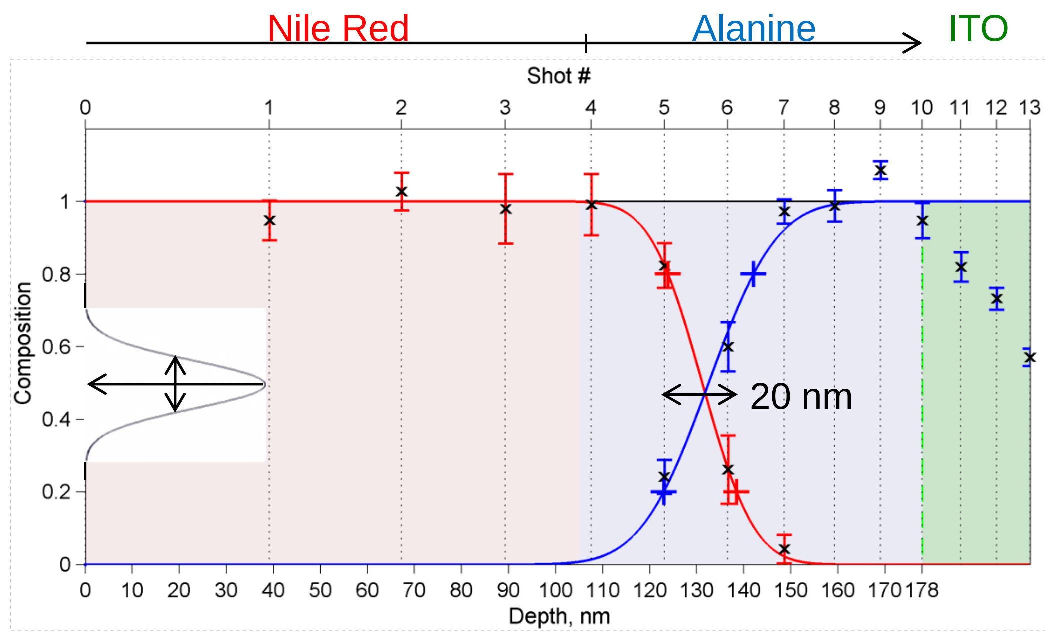


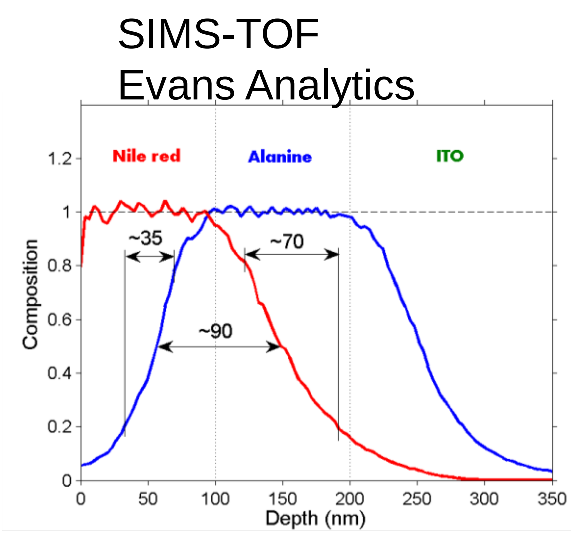
I. Kuznetsov et al. Nature Comm., 6, 6944,(2015)

T. Green, et al., *J. of Analytical Atomic Spectrometry, 32, 1092, (2017)*

Depth resolution of 20 nm is achieved on organic multilayers

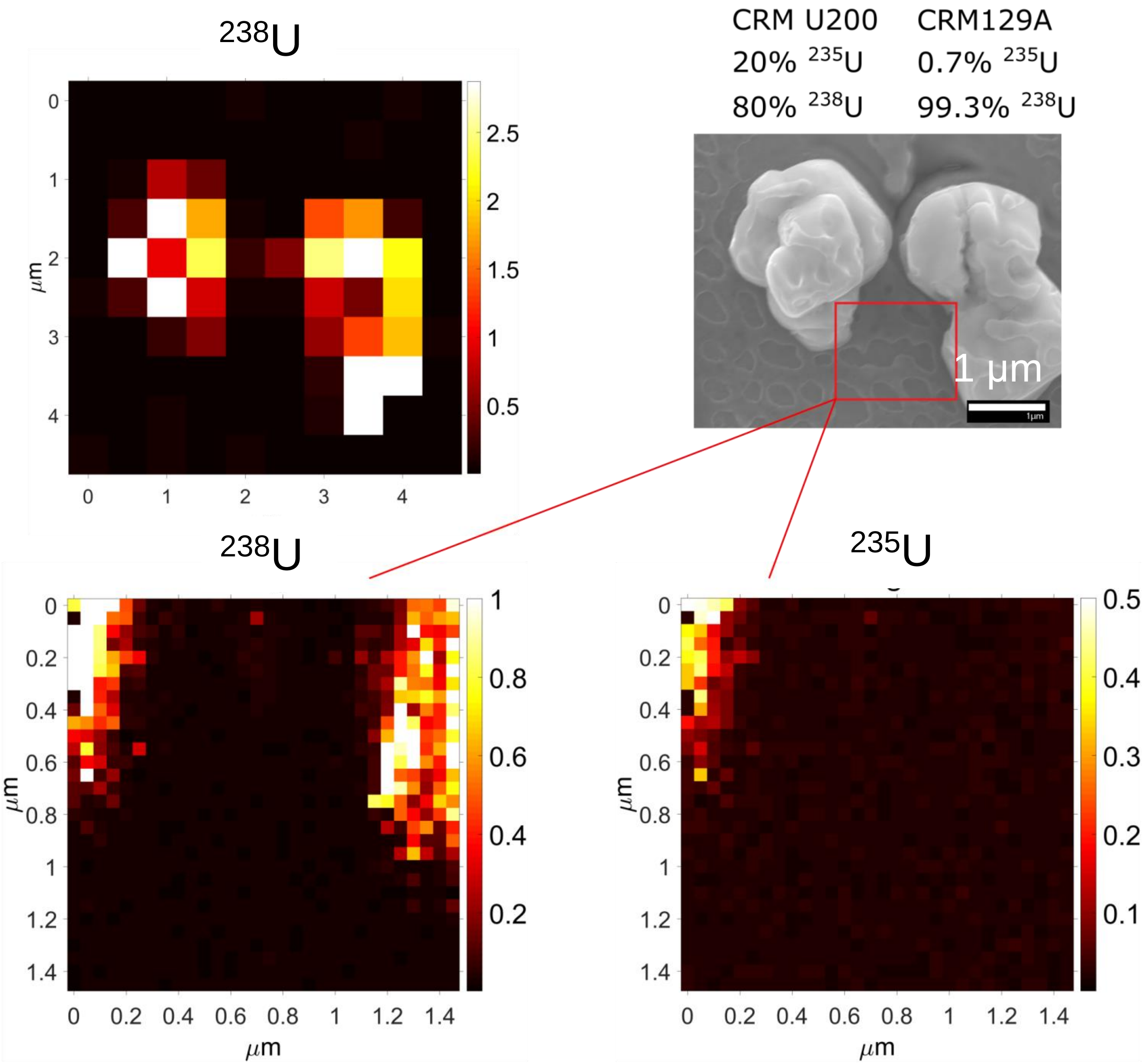






I. Kuznetsov et al, Nature Communications, ***6****, 6944, (2015)*

2D Imaging of uranium micron size particles by EUV TOF MSI reveals isotopic content



Measured:

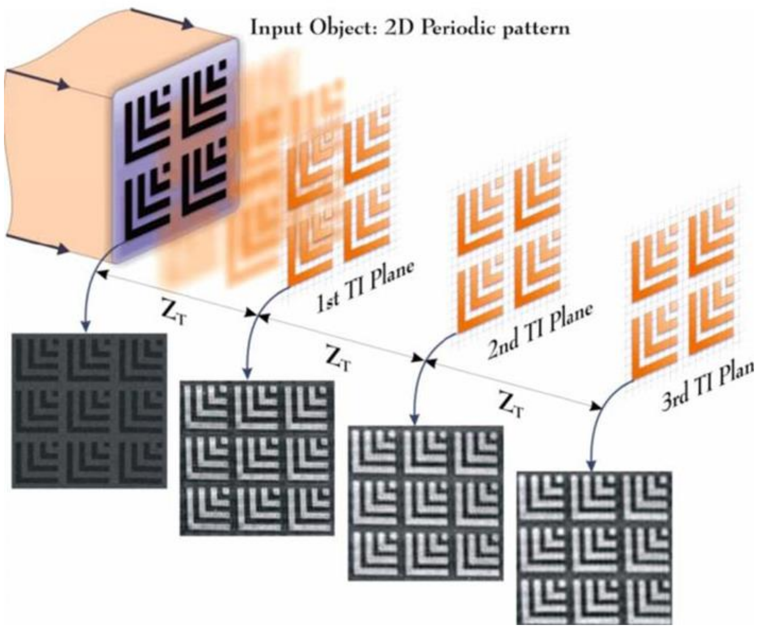
$^{235}U/^{238}U$ ratio of 0.248 (±0.0014)

Expected value is

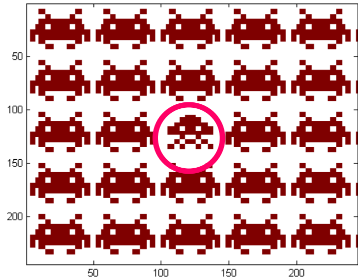
0.2513 (±0.0003) (U200 standard)

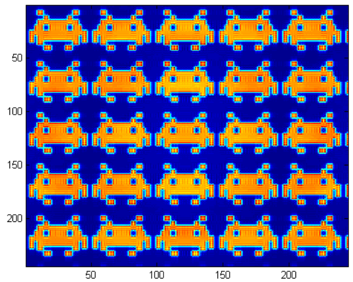
Collaboration with Pacific Northwest Laboratory

Talbot lithography: Coherent illumination of a periodic mask prints arrays of arbitrary features error-free

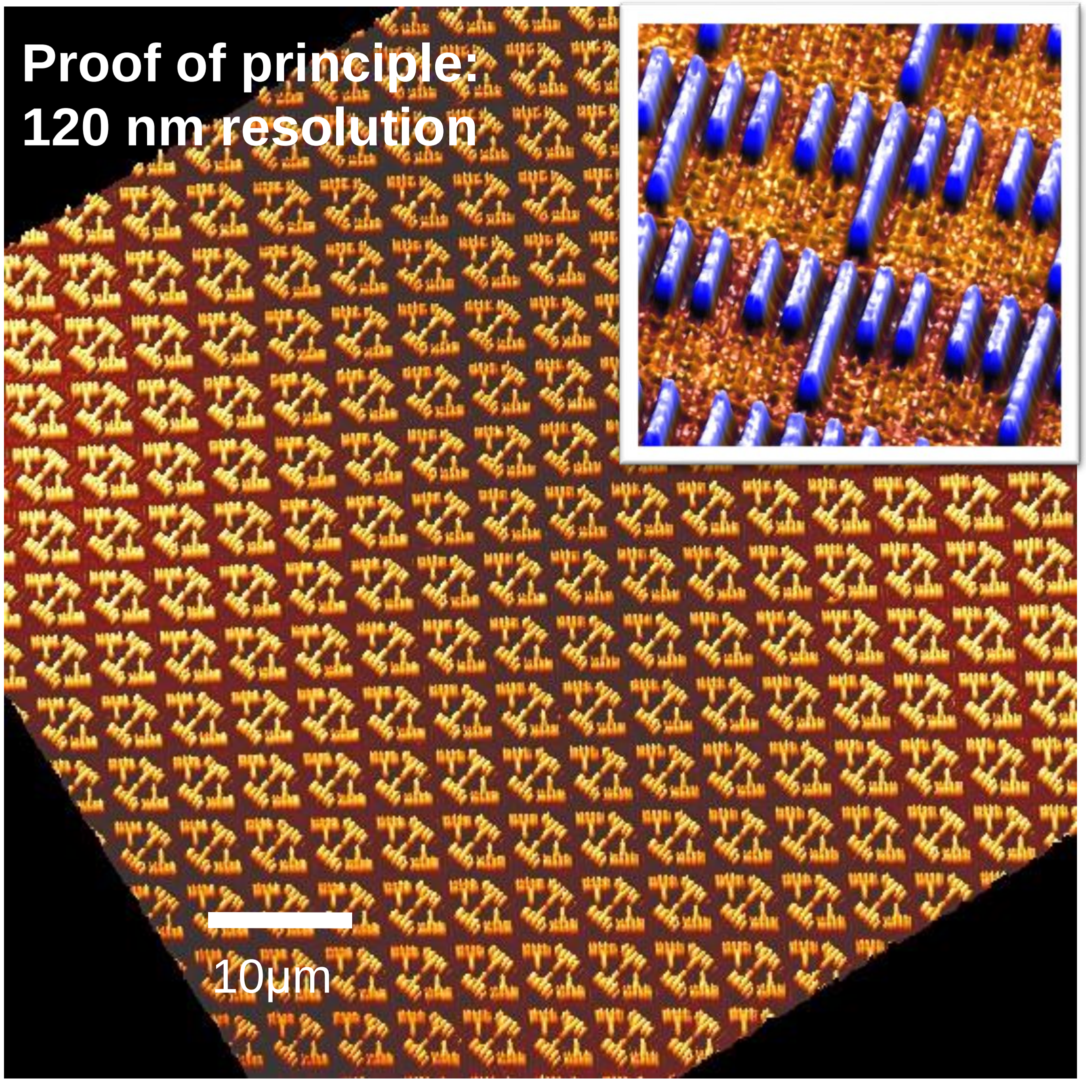


Error free printing





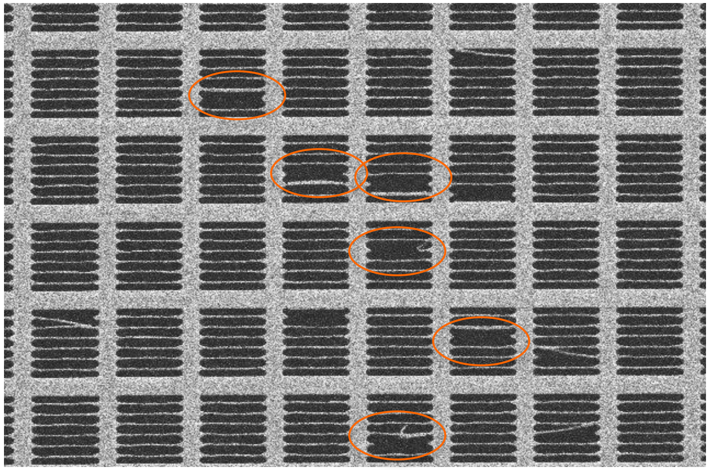
M. Marconi, F. Cerrina, et al. (2009)



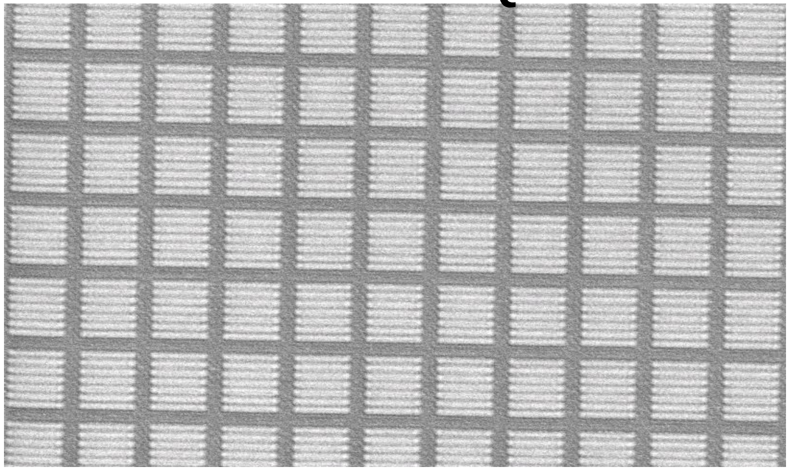
A. Isoyan et al. JVST B 37, 2931, (2009), L. Urbanski et al. Optics Letters (2012)

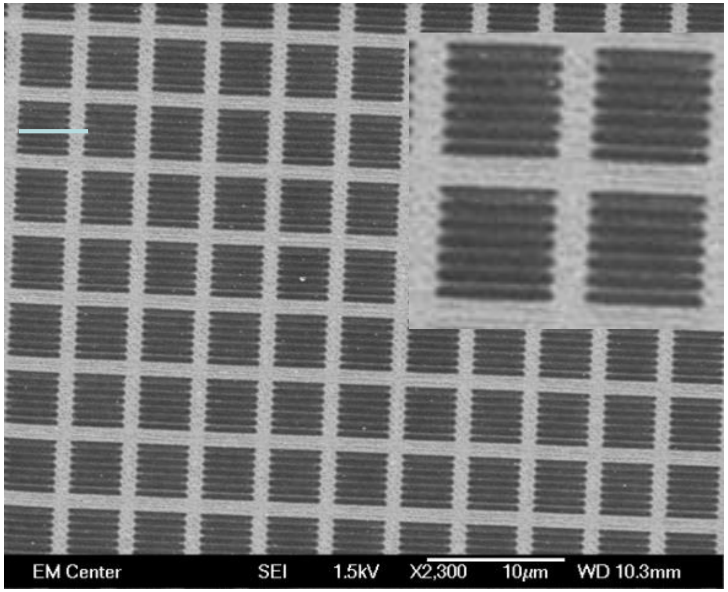
Error-Free Printing of Periodic metallic structures

Talbot Mask



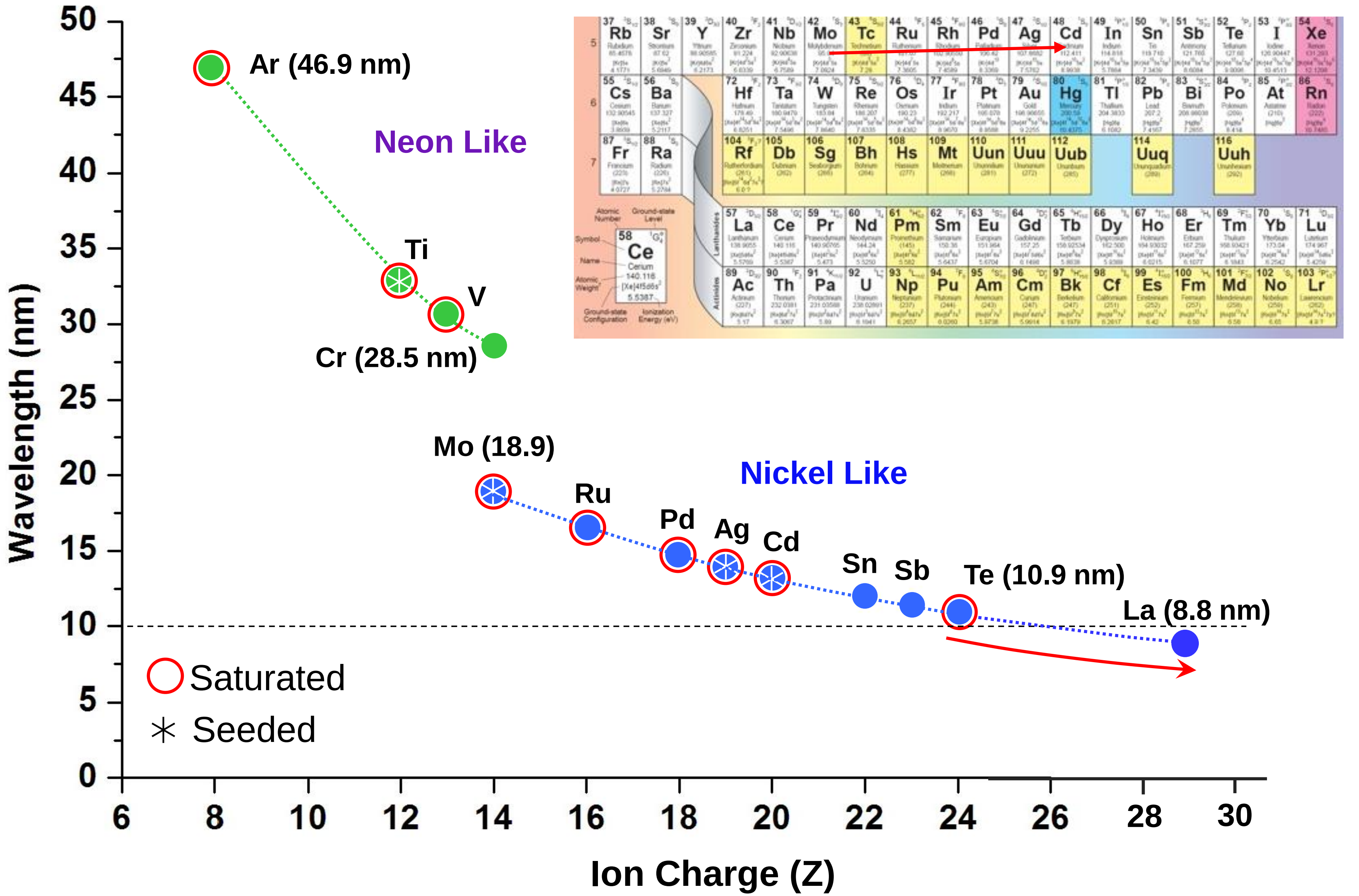
Print in HSQ



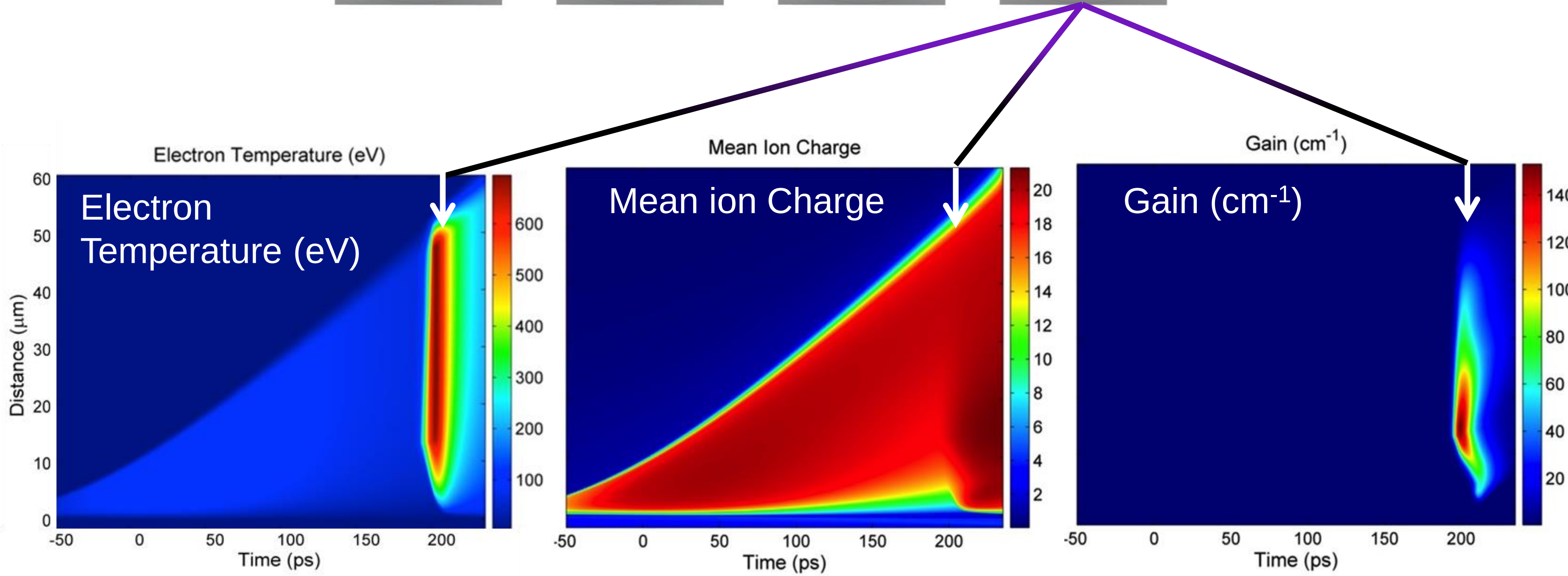


Grating etched in Au 500/600 lines/spaces

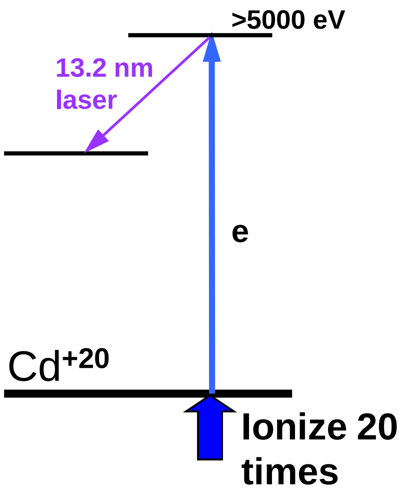
Scaling to shorter wavelengths



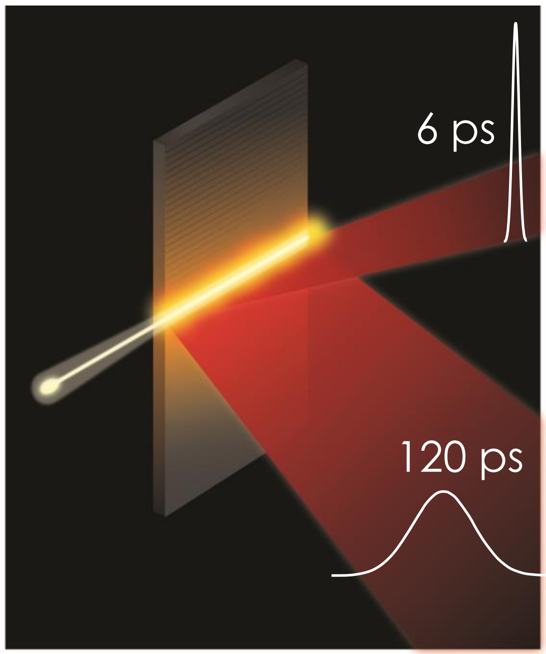
Simulation showed gain-saturated amplification at 13.2 nm in Ni-like Cd can be achieved with ~ 1 J pump



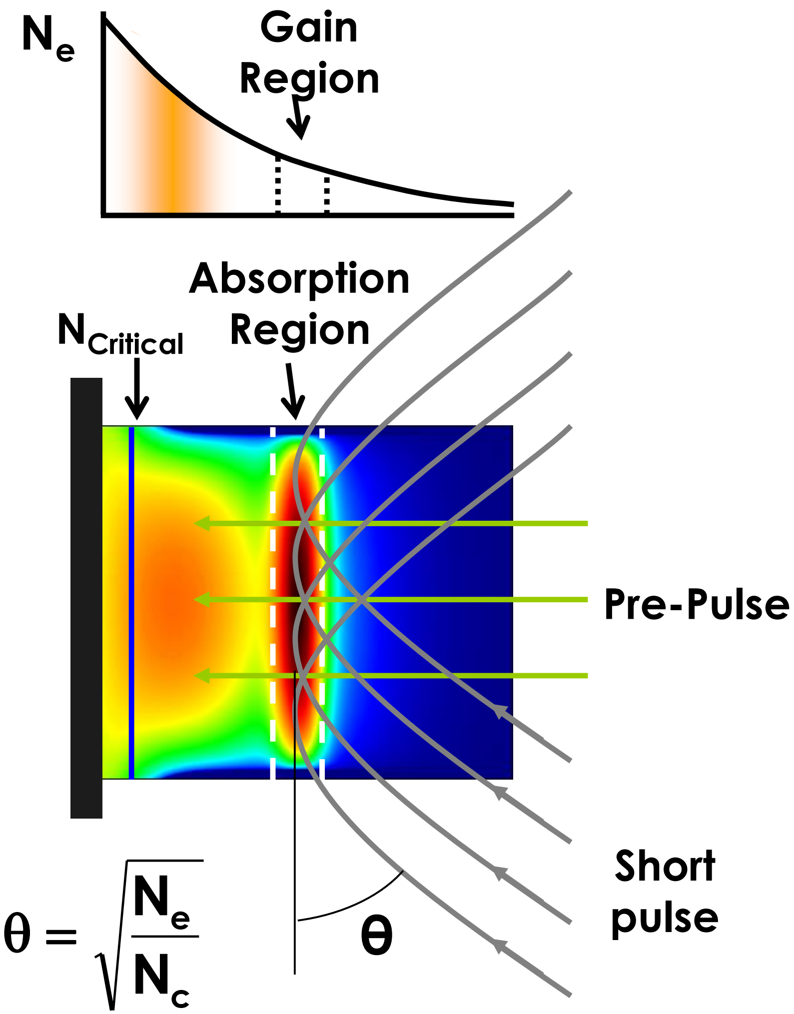
EUV lasers excited by rapid heating of plasmas with short laser pulses



Laser Pumping Geometry

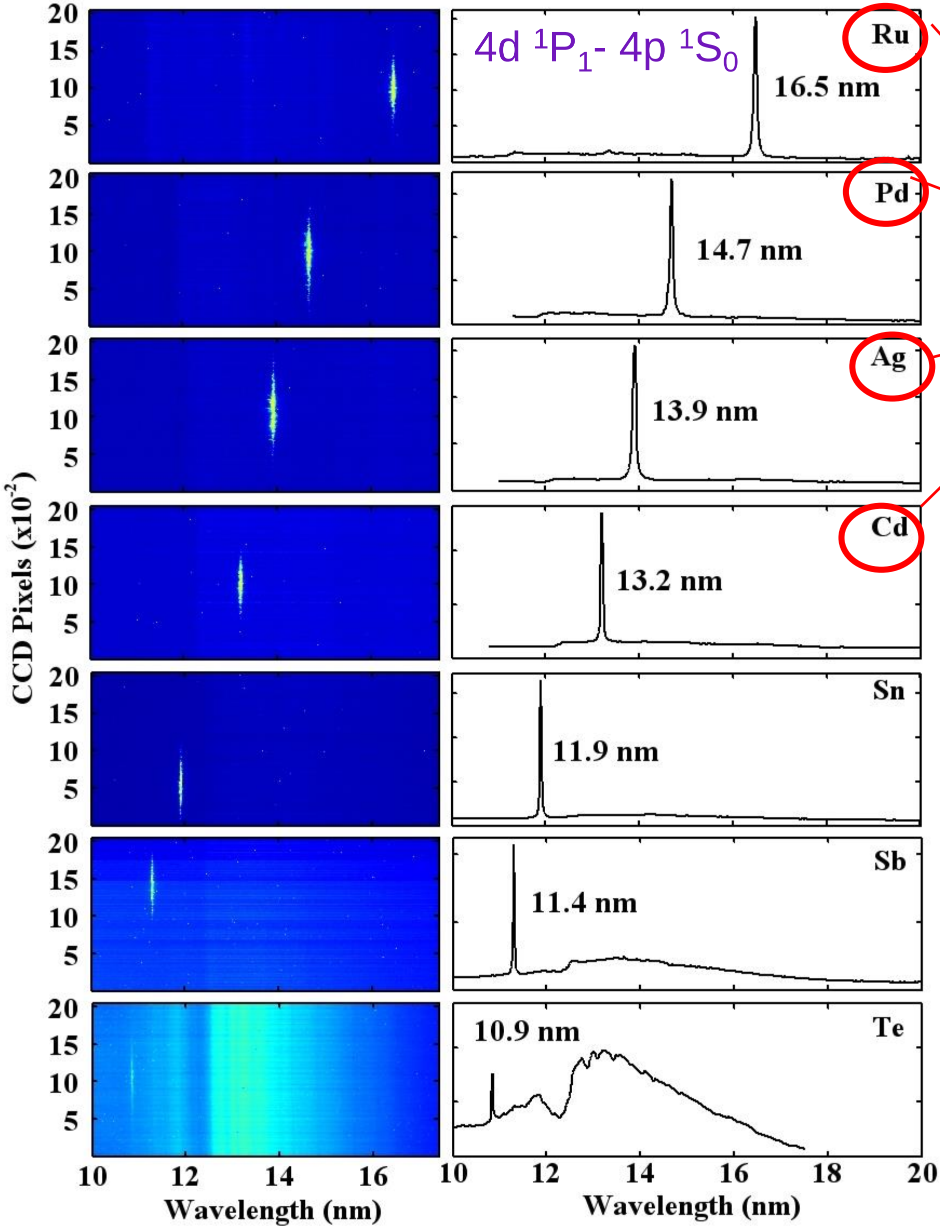


Grazing incidence allows for efficient heating of plasma region with optimum electron density

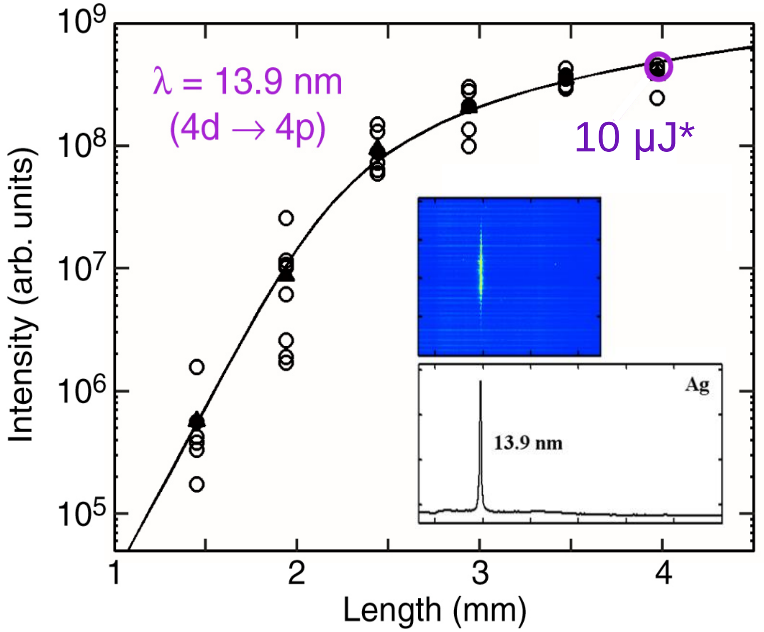


R. Keenan et al, Phys. Rev. Lett. 94, 103901 (2005) ; B.M. Luther et al, Opt. Lett. 30, 165 (2005); Transient excitation: P. Nickels, V. Shlyaptsev et al. Phys. Rev.Lett. 78,2 748, (1997)

High repetition rate table-top EUV lasers in transitions of Ni-like ions down to 10.9 nm



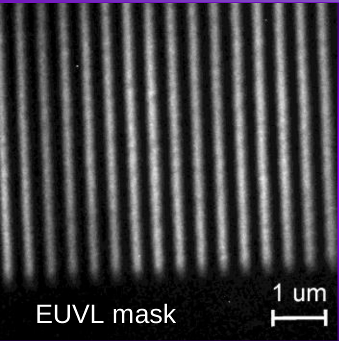
Gain saturated operation demonstrated



*Y. Wang et al, Phys. Rev. A **72**, 053807 (2005)*

D. Martz et al. Optics Lett. **35, 1632 (2010)*

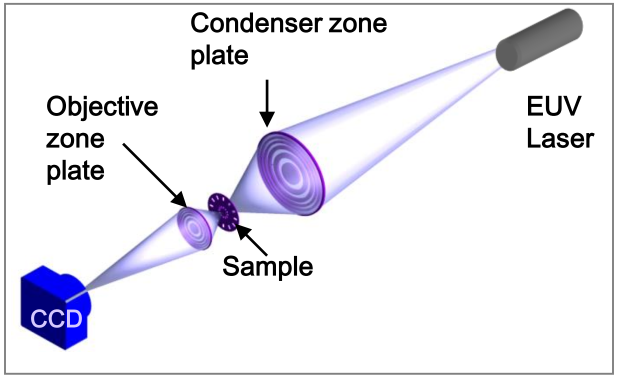
λ=13.2 nm microscope for at-wavelength aerial mask inspection and broad area imaging of nanostructures

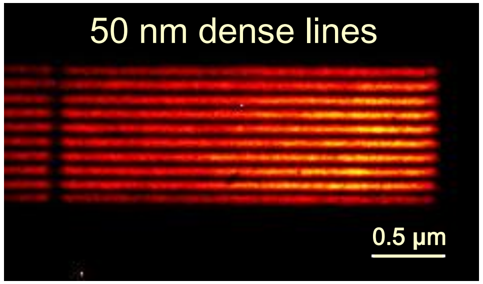


- Uses output from 13.2 laser
  J.J. Rocca et al., Opt. Lett. Vol. 30, 2581 (2005); Y. Wang et al., Phys. Rev. A 72, 5 (2005)
- Captures images with large field of view with exposures of 20-90 seconds

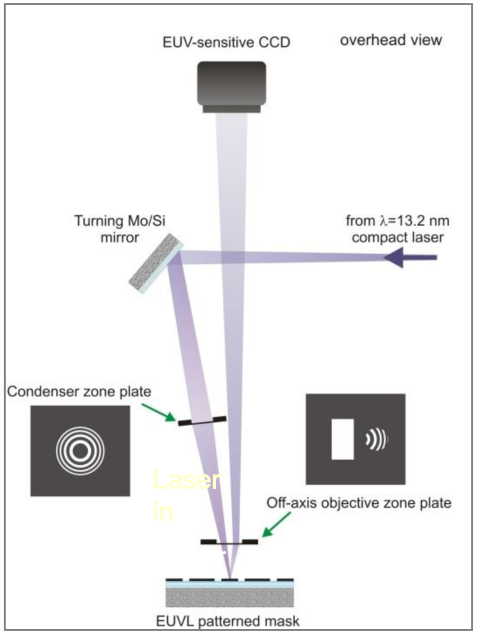
TRANSMISSION

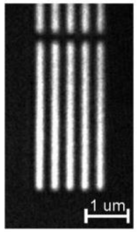
- **Spatial resolution: better than 38 nm**

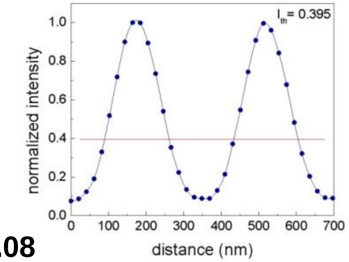




G. Vaschenko, et al Optics Letters, vol 31, 1214 (2006)



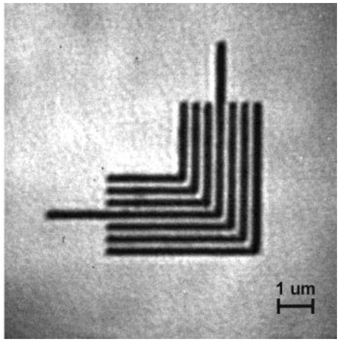




LER/CD=0.08

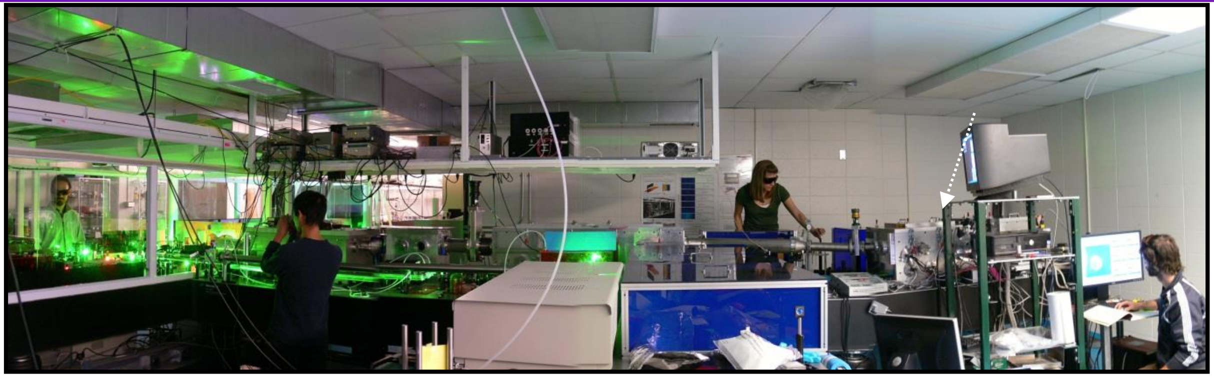
REFLECTION

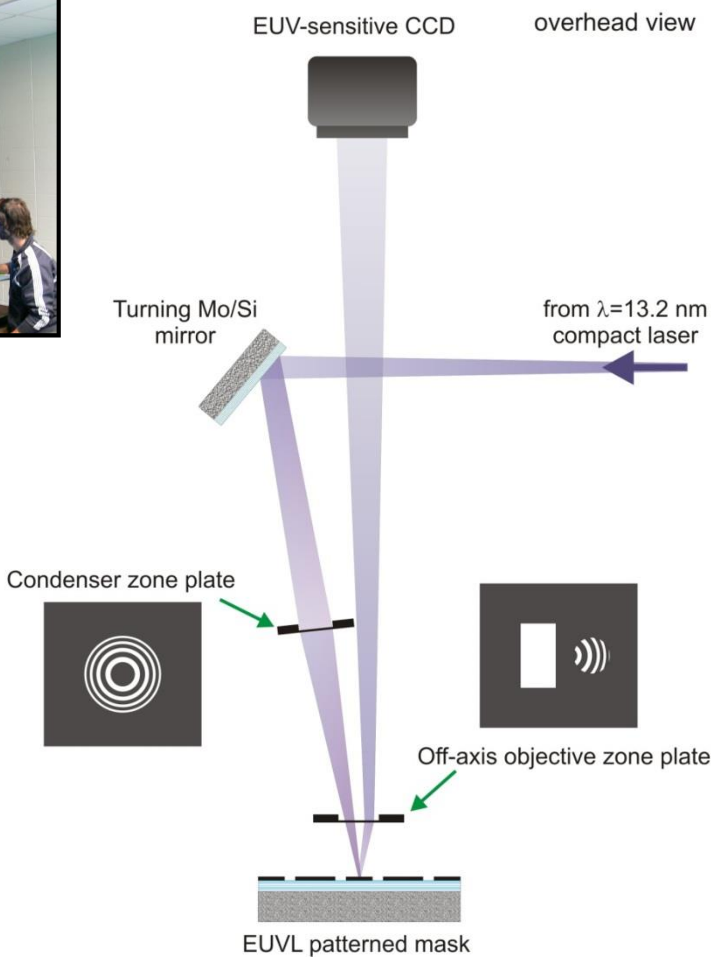
- **Zone plate microscope for at wavelength defect inspection**
- **Illumination emulates EUVL stepper**
- **Spatial resolution: 55 nm**



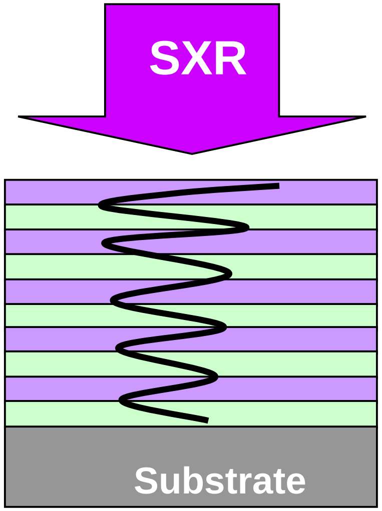
F. Brizuela et al, Optics Letters vol. 34, 271, (2009)

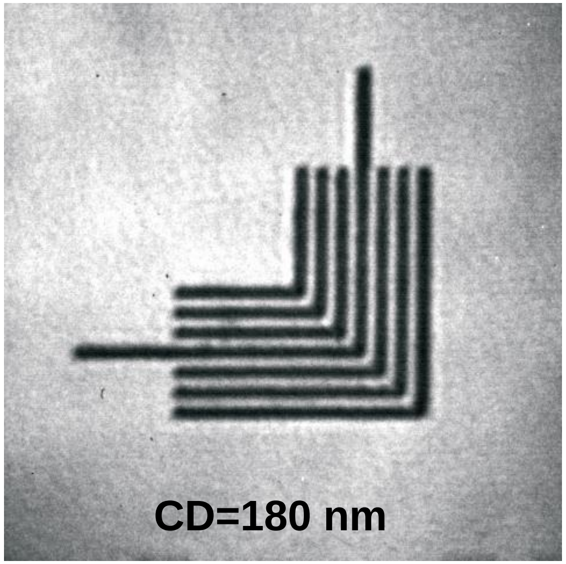
13.2 nm laser-based microscope for defect inspection in EUV lithography masks





λ= 13.2 nm resonant with Mo/Si coatings in extreme ultraviolet lithography masks



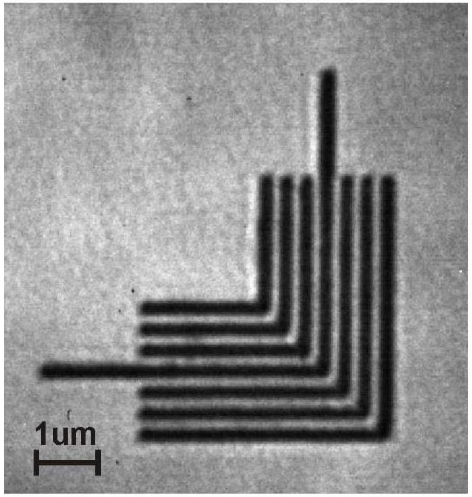


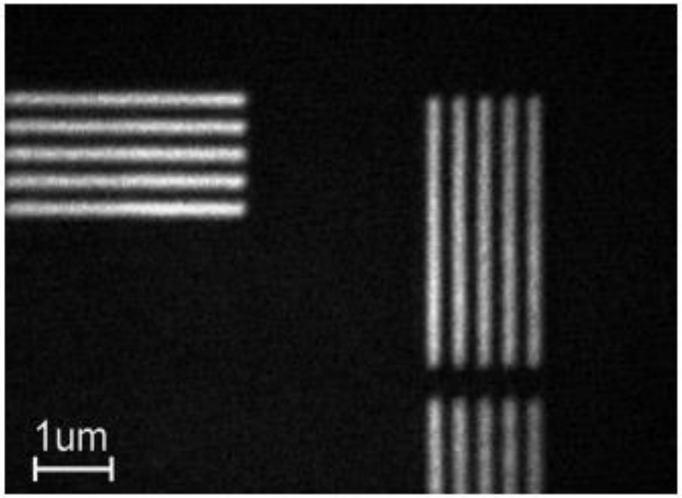
EUV Optics from CXRO, Berkeley

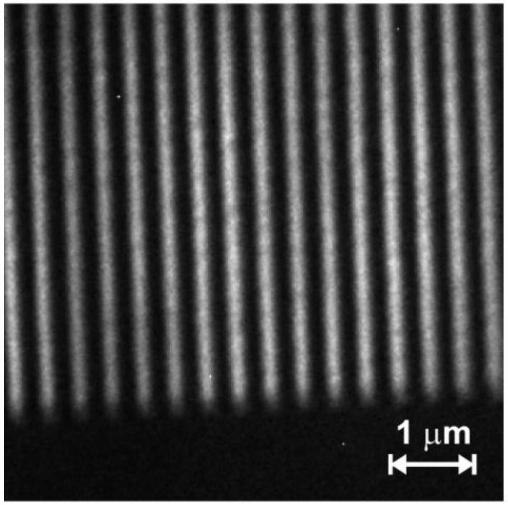
F. Brizuela et al., *Optics Express* ***18****, 14467, (2010)*

EUV MASK IMAGES

Spatial resolution: 55 nm half-pitch



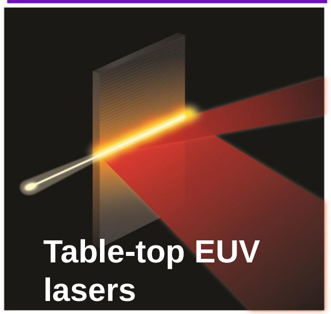




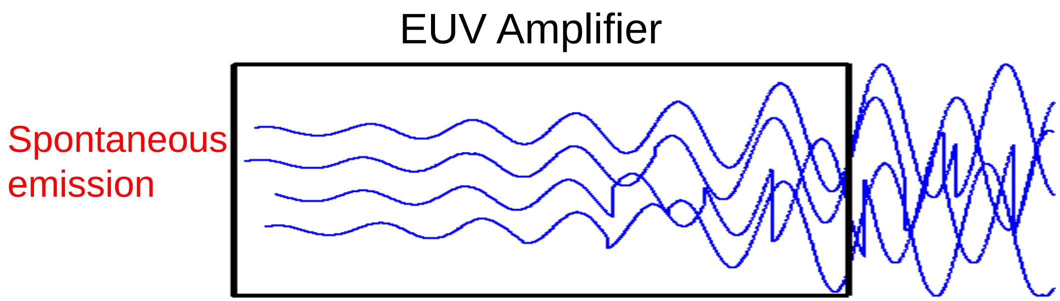
LER< 10% CD

F. Brizuela et. al., Opt. Exp. ***14****, 14467 (2010)*

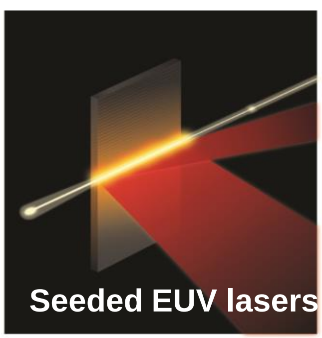
EUV lasers self-seeded by spontaneous emission noise have poor temporal coherence

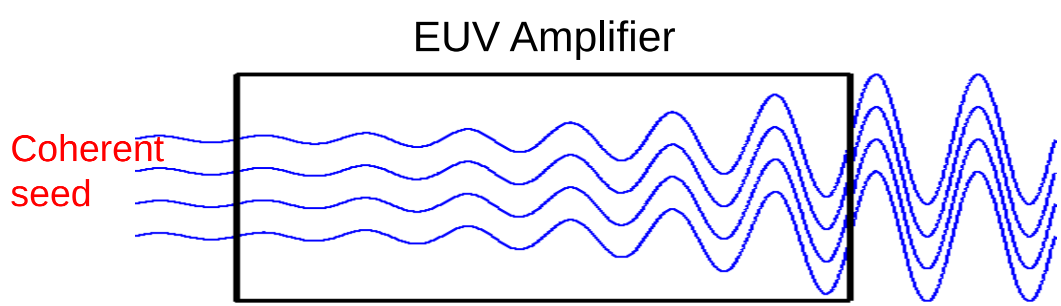


Self-seeded



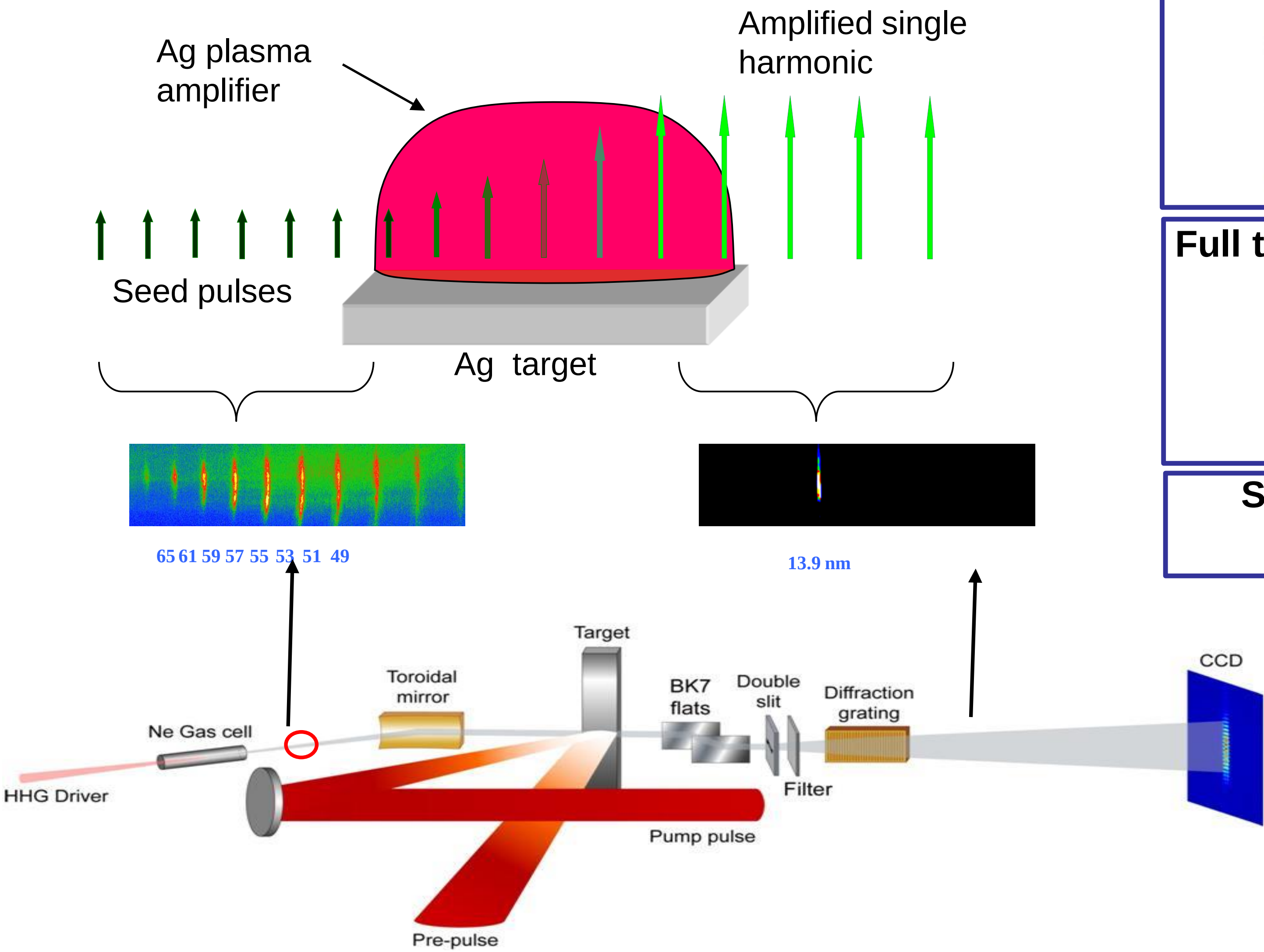
Injection-seeded



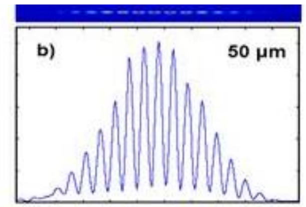


Seed pulses can be greatly amplified preserving or even improving their properties

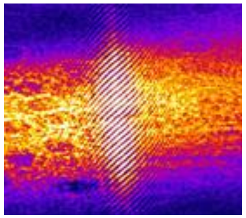
Injection-seeding SXR Lasers have full phase-coherence and shorter pulsewidth



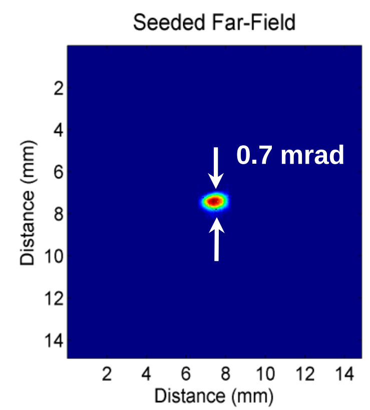
Full spatial coherence



Full temporal coherence

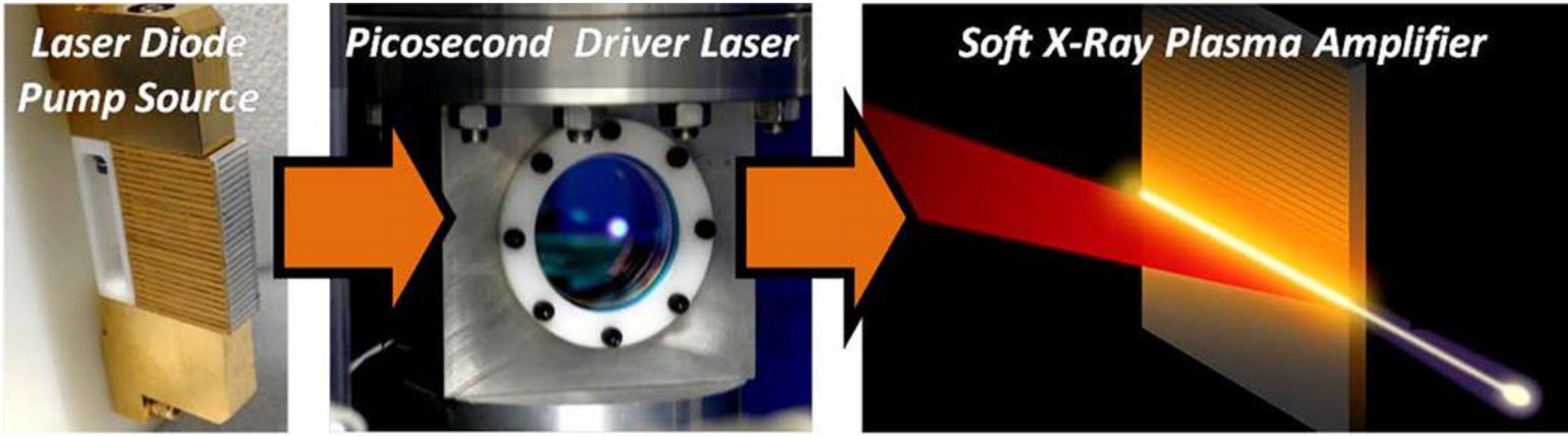


Shorter pulsewidth
(1.13±0.47)ps



T. Ditmire et al. Phys. Rev. A. ***51****, R 4337, (1995); P. Zeitoun et al. Nature,* ***431****, 427, (2004) ;*
Y. Wang et al. Phys. Rev. Lett, ***97****, 123901 (2006) Y. Wang et al. Nature Photonics,* ***2****, 94, (2008)*

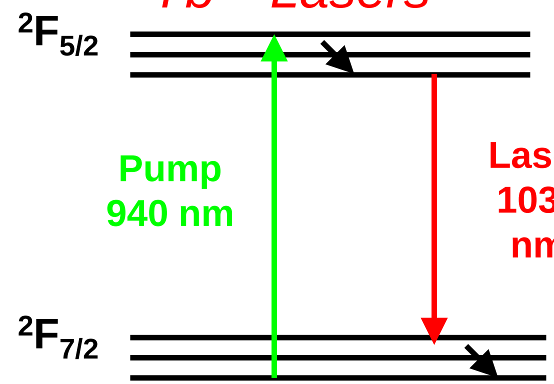
High repetition rate, diode-pumped table-top soft x-ray lasers



Laser Diode Pumping Advantages

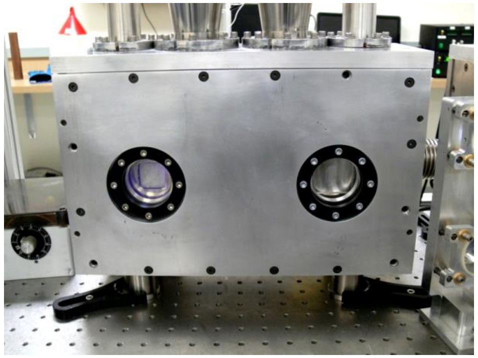
- Highly efficient
  - >50% Electrical efficiency
- Narrow bandwidth
  - Efficiently pump a single transition
- Directional
  - End-pumping
- Very high average power
  - Allow high repetition rate
- Compact

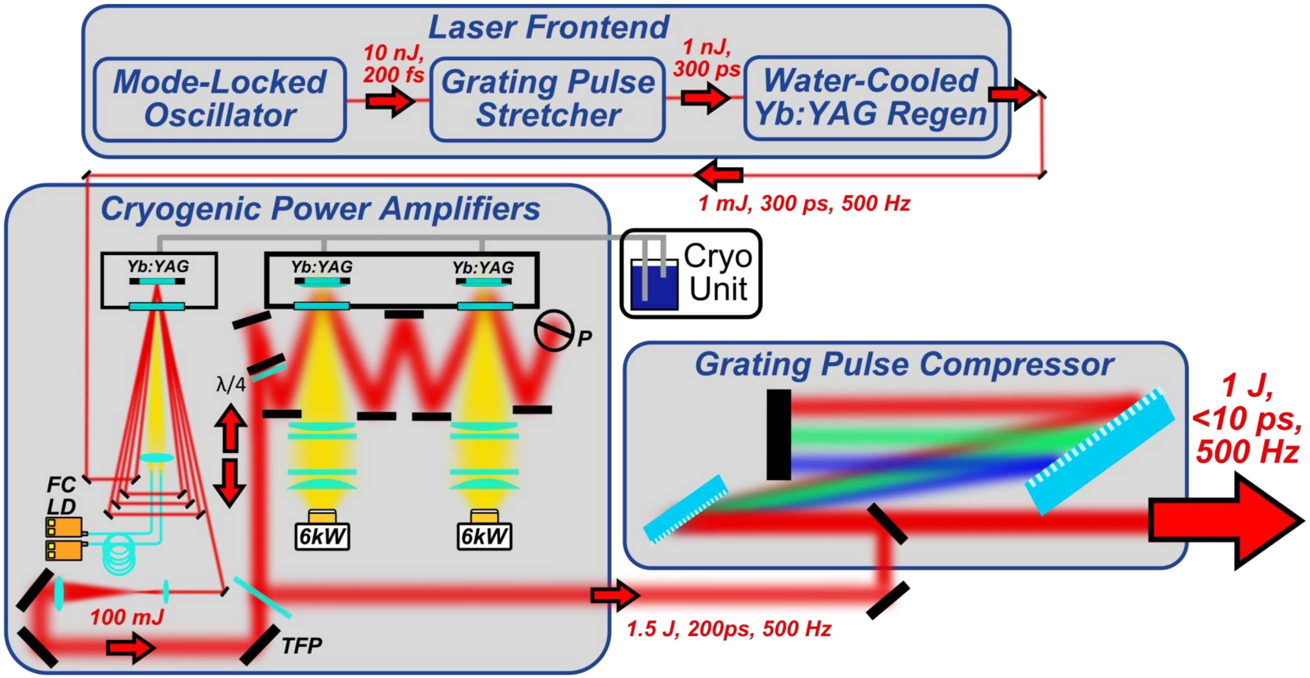
Yb^{+3} Lasers



- Absorption bands at InGaAs wavelengths
- Small quantum defect (<10%)
- Long lifetime for high energy storage

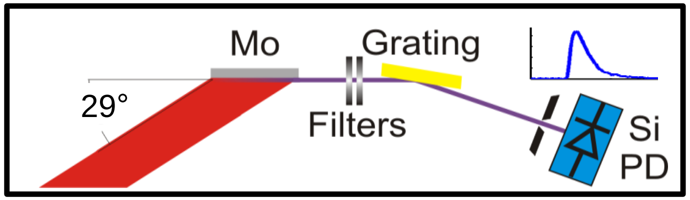
Beyond 100 Hz Repetition Rate: 500 Hz
Compact High Energy, High Power Pump Laser

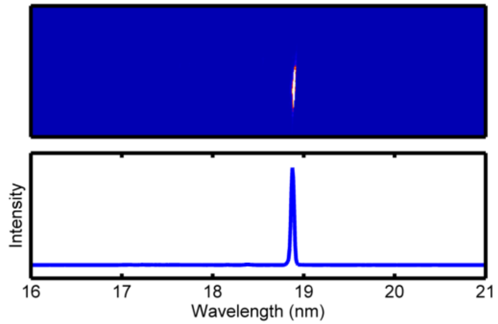


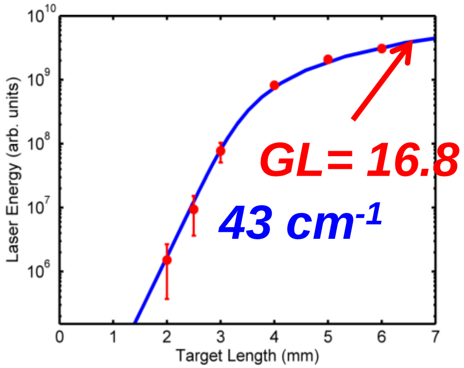


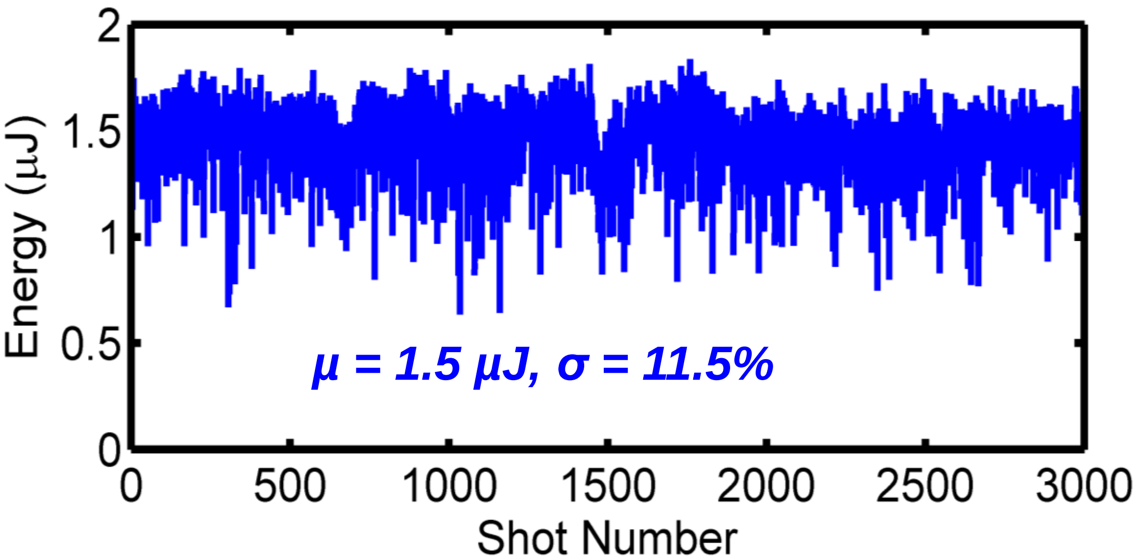
C. Baumgarten, et al., *Opt. Lett.* **41** (2016).

Demonstration of bright 18.9 nm laser at 100 Hz repetition rate





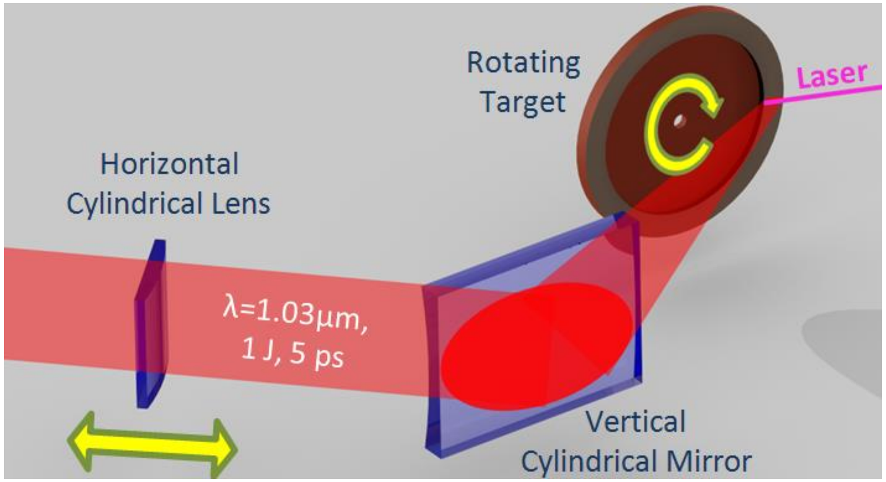


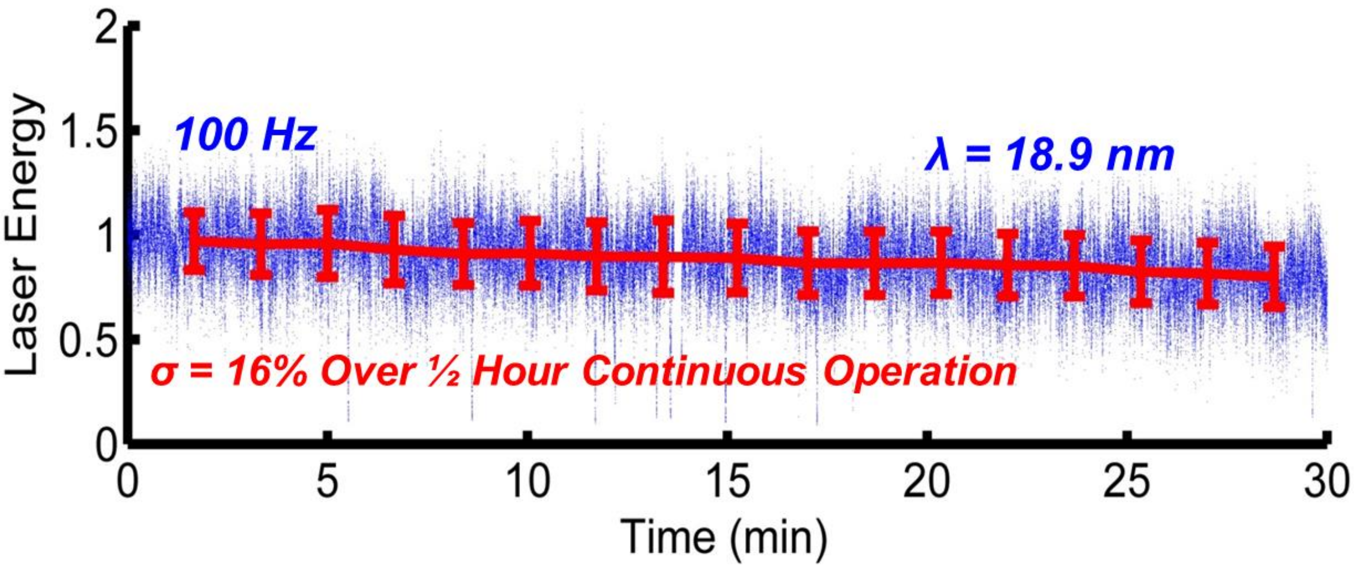


λ = 18.9 nm Laser Average Power: **0.2 mW**

B. Reagan, et al., Opt. Lett. 37 (2012).

λ=18.9 nm: 10^5 Consecutive EUV Laser Shots at 100 Hz repetition rate



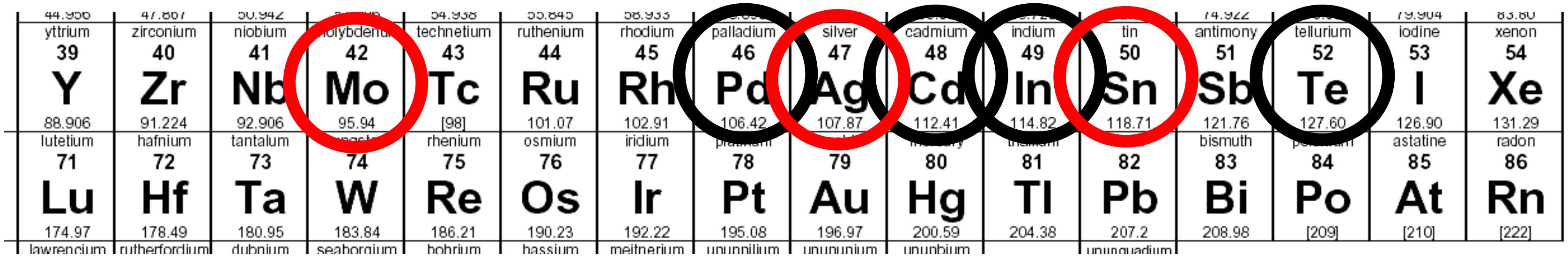


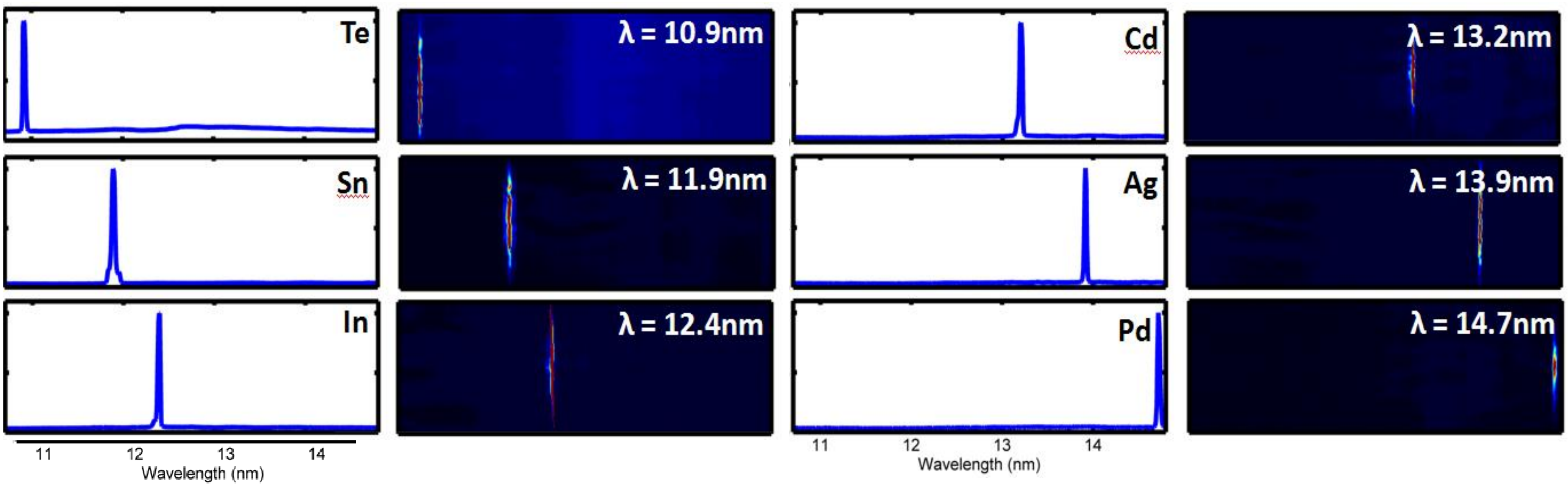
B. Reagan et al. Optics Express, 21, 28320 (2013)

Extending diode-pumped lasers to λ = 10.9 nm

Colorado State University

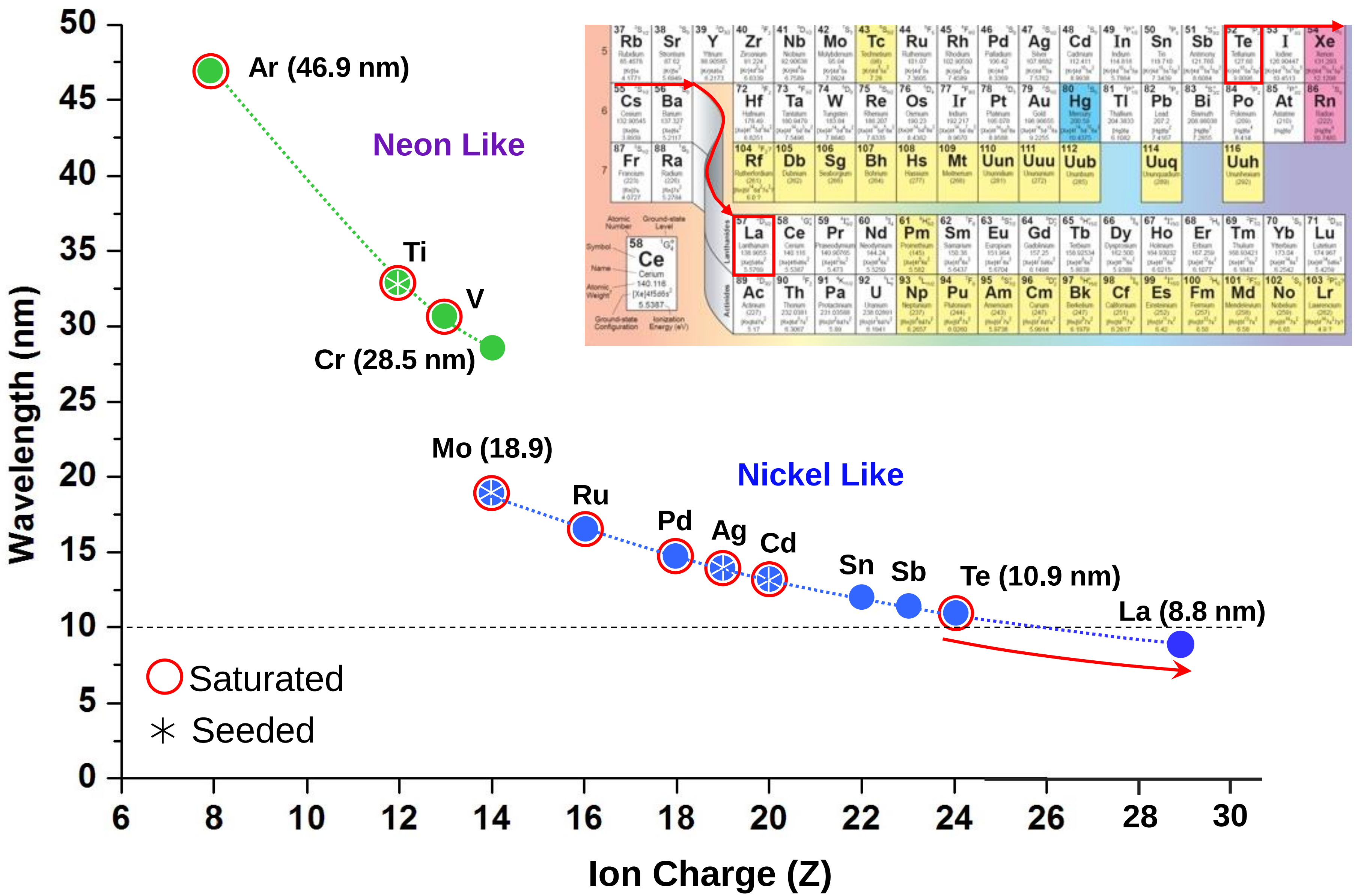
Ni-like ions



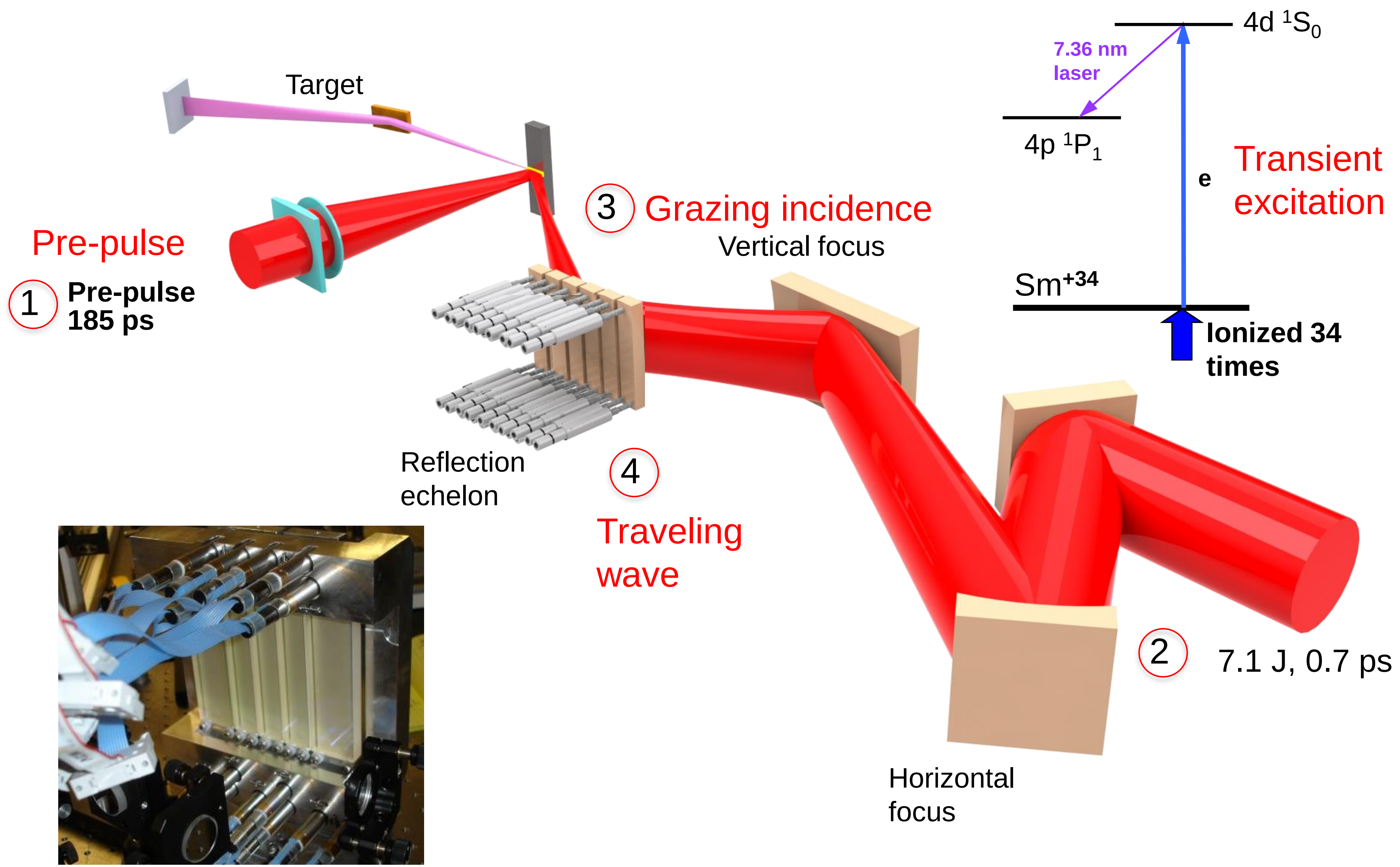


- **0.2 mW** at **λ = 18.9 nm**
- **0.1 mW** at **λ = 13.9 nm**

Extension of gain-saturated table-top SXRL to sub-10 nm wavelengths using lanthanide ions

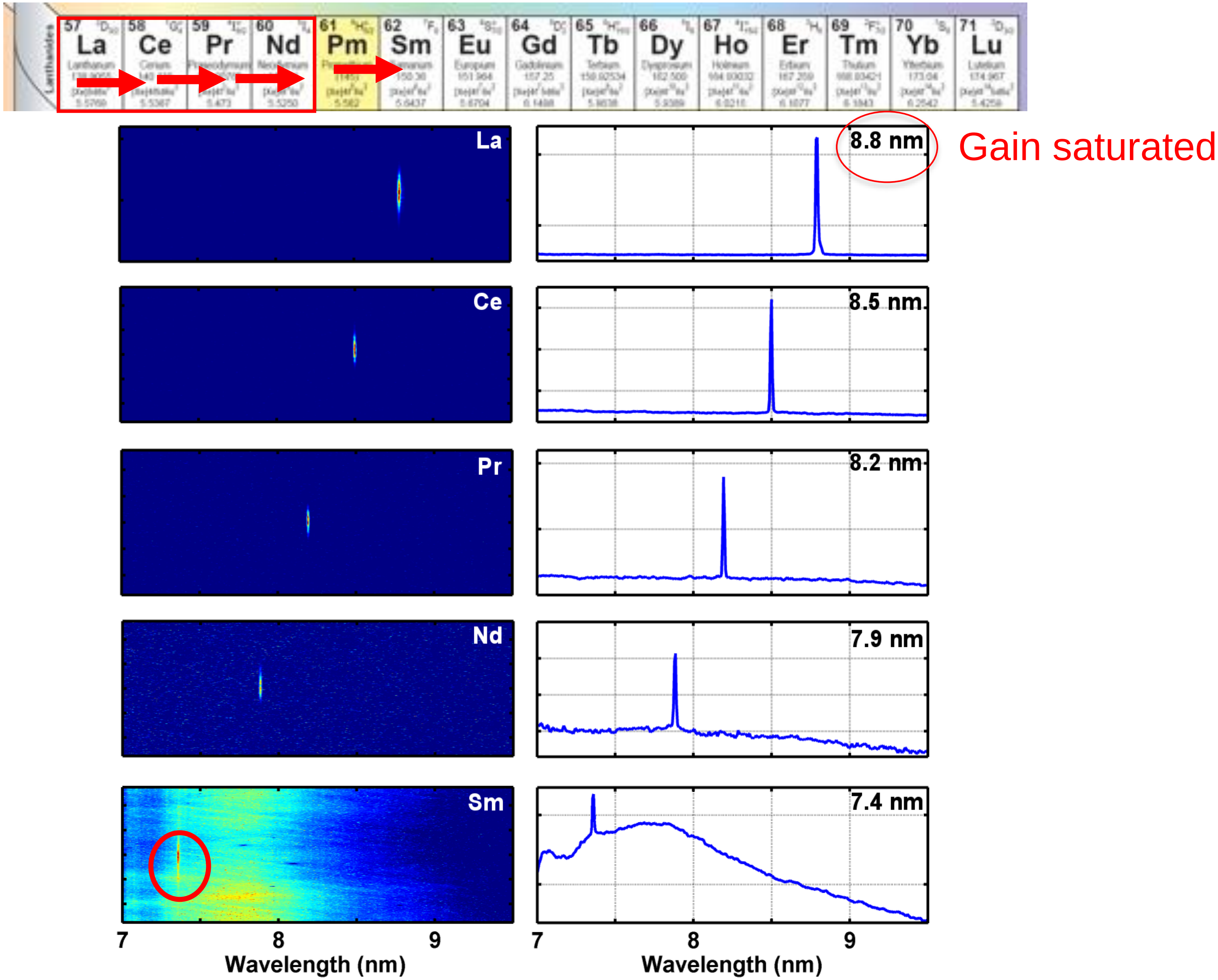


Gain-saturated sub-10 nm table-top lasers



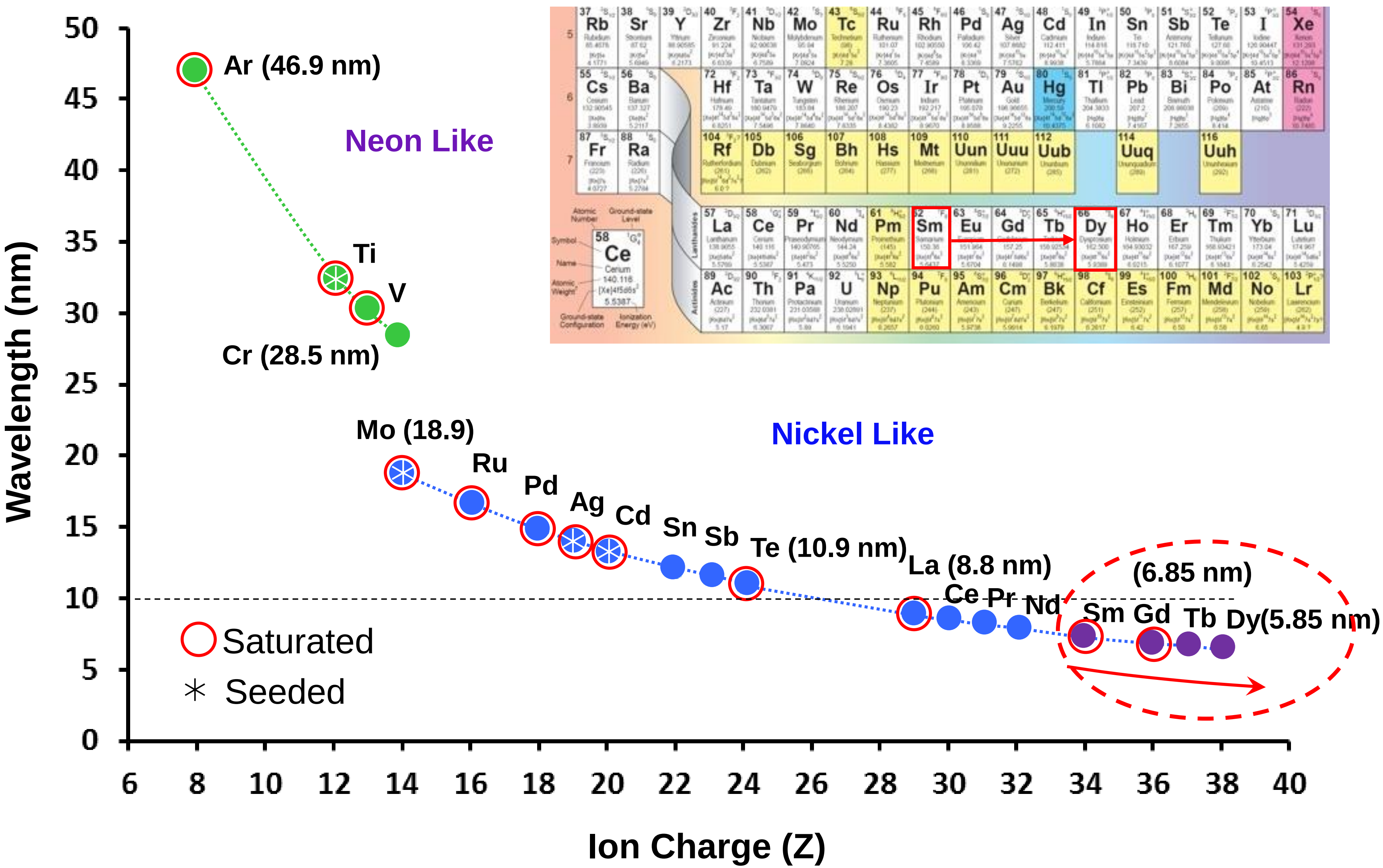
Lasing in transitions down to 7.36 nm

Nickel-like lanthanide ions 4d$^1S_0$- 4p$^1P_1$

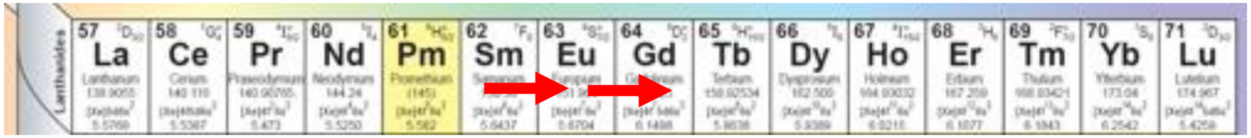


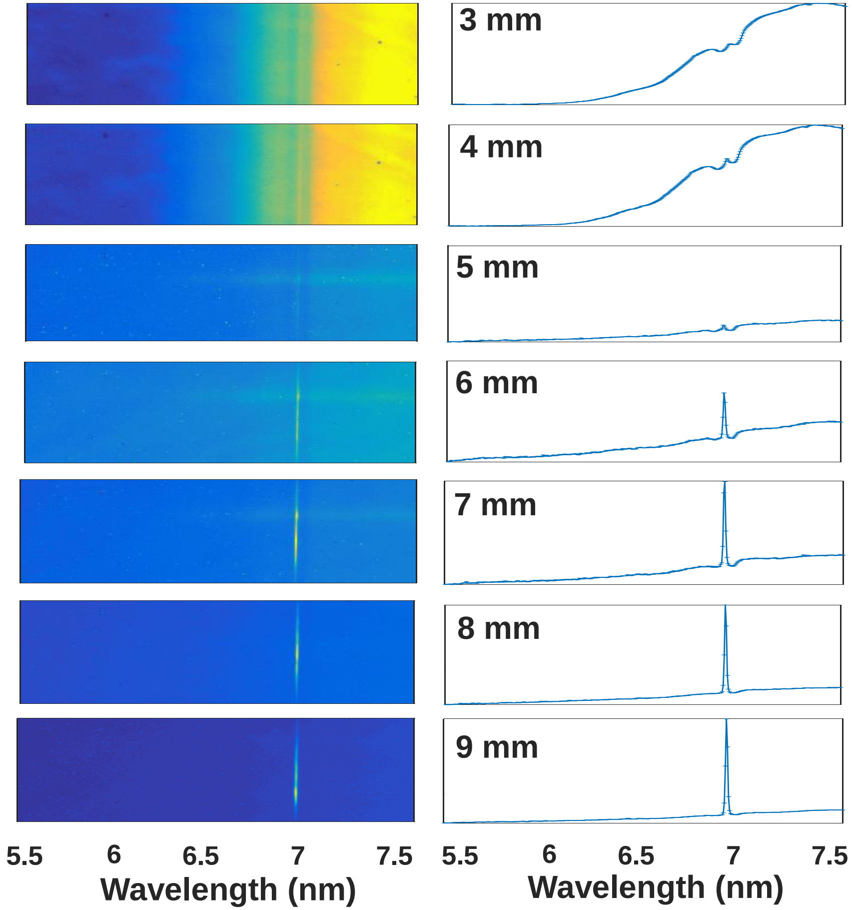
D. Alessi et al. Phys. Rev. X ,1, 021023

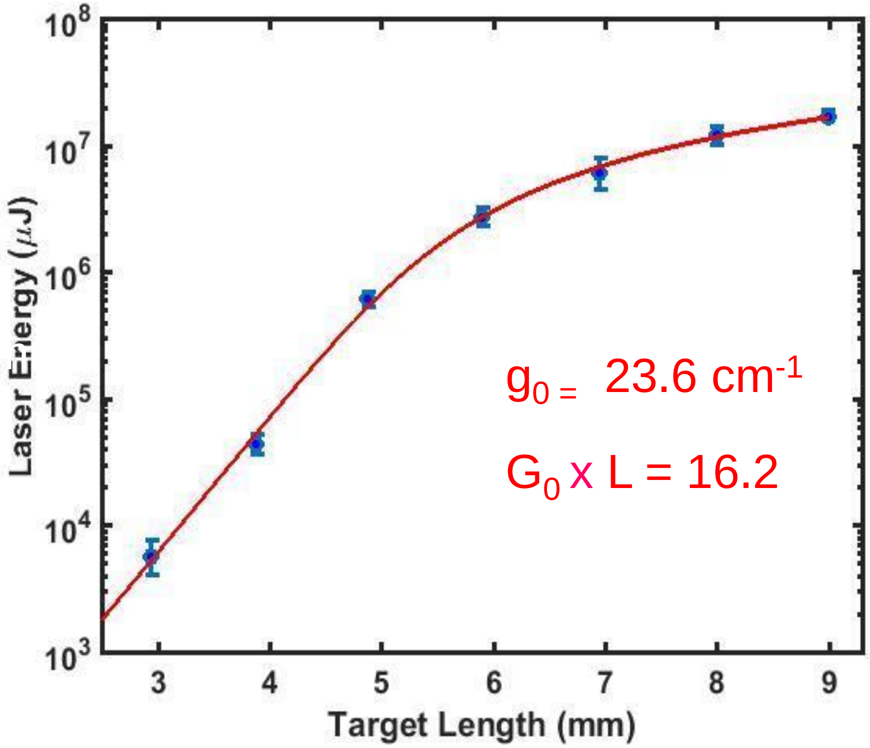
Extension of gain-saturated table-top SXRL to sub-7 nm wavelengths using lanthanide ions



Gain saturation in Ni-like Gd at 6.86 nm

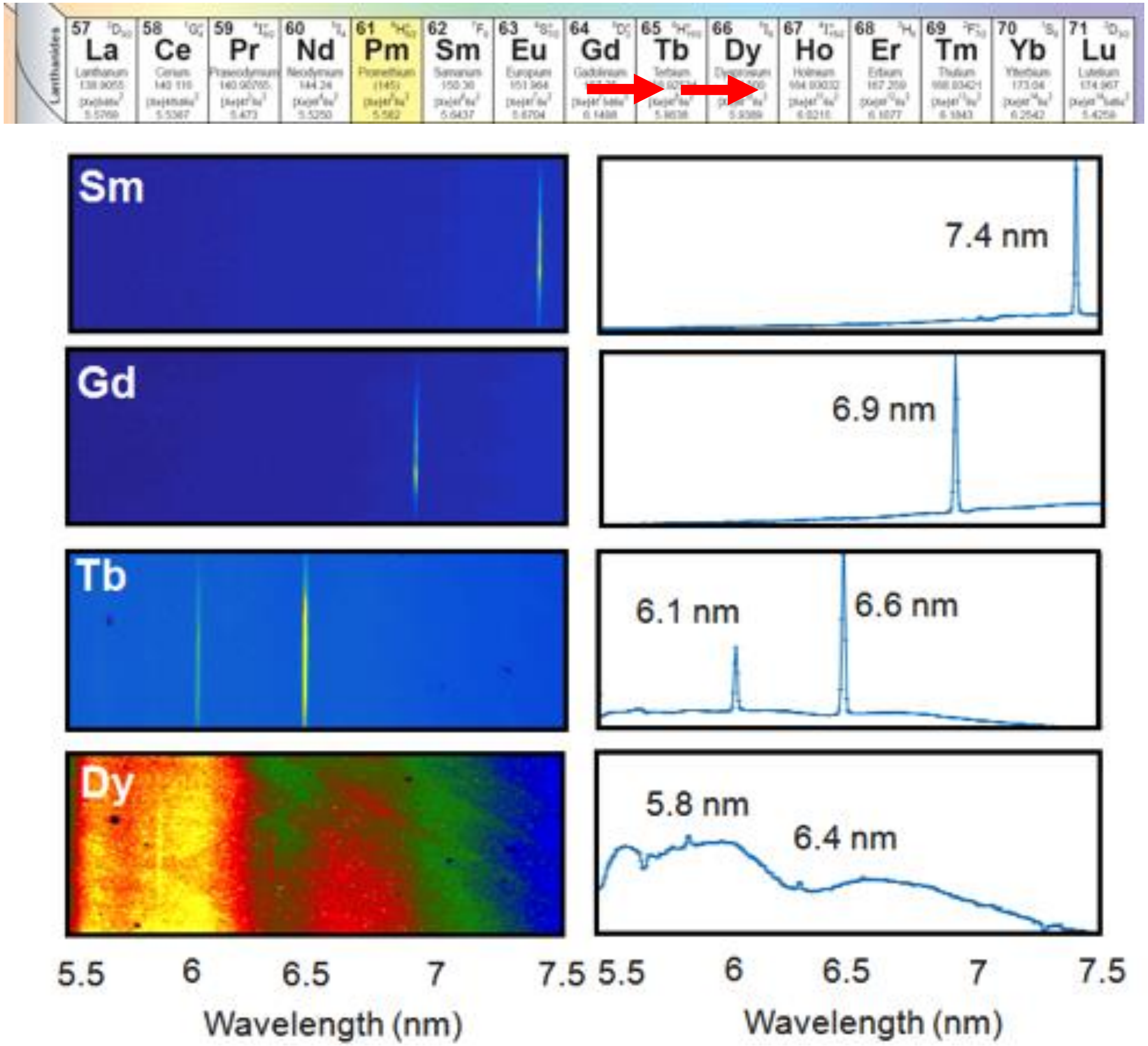




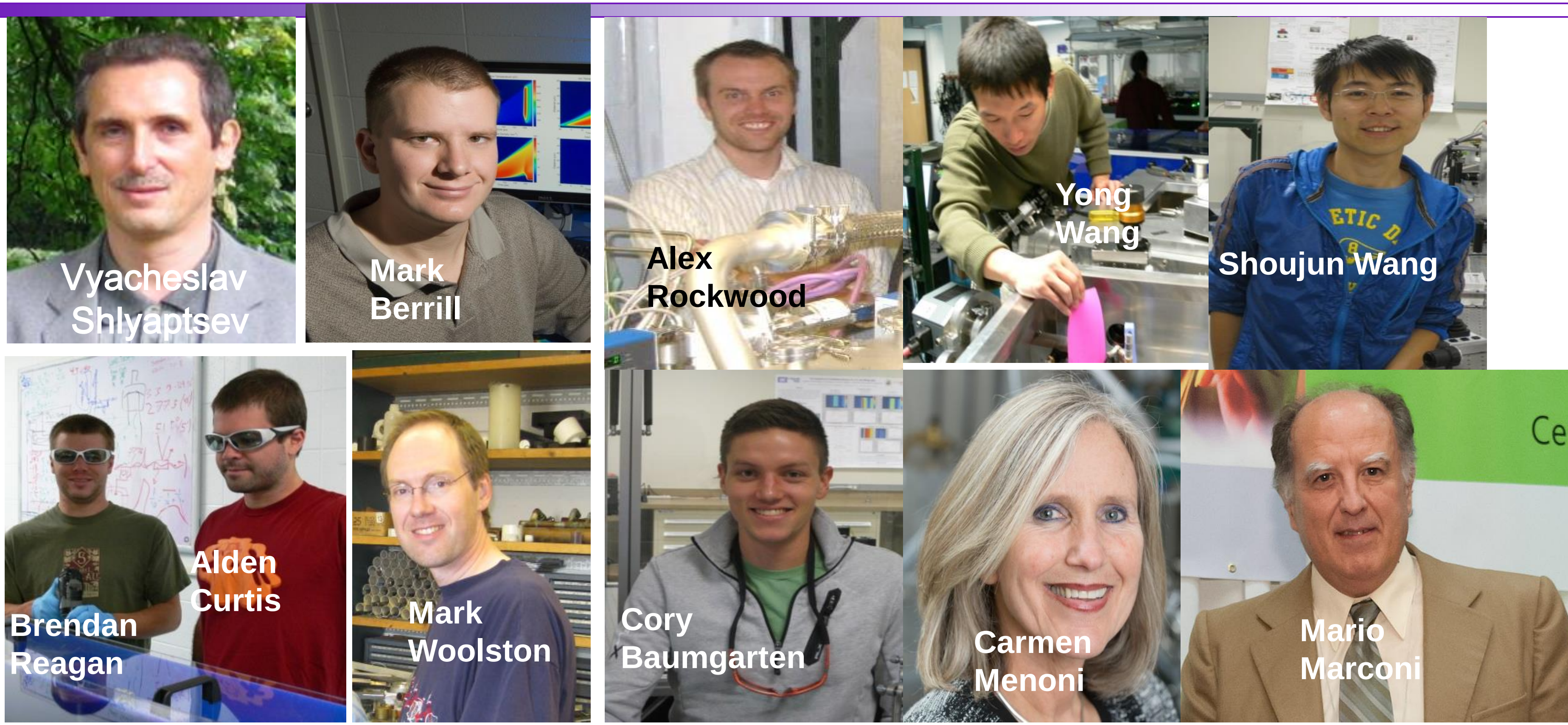


Energy on target = 14 J , pre-pulse width= 185 ps, short pulse width= 0.7 ps , 40% in pre-pulse

Laser amplification down to 5.8 nm (Ni-like Dy)



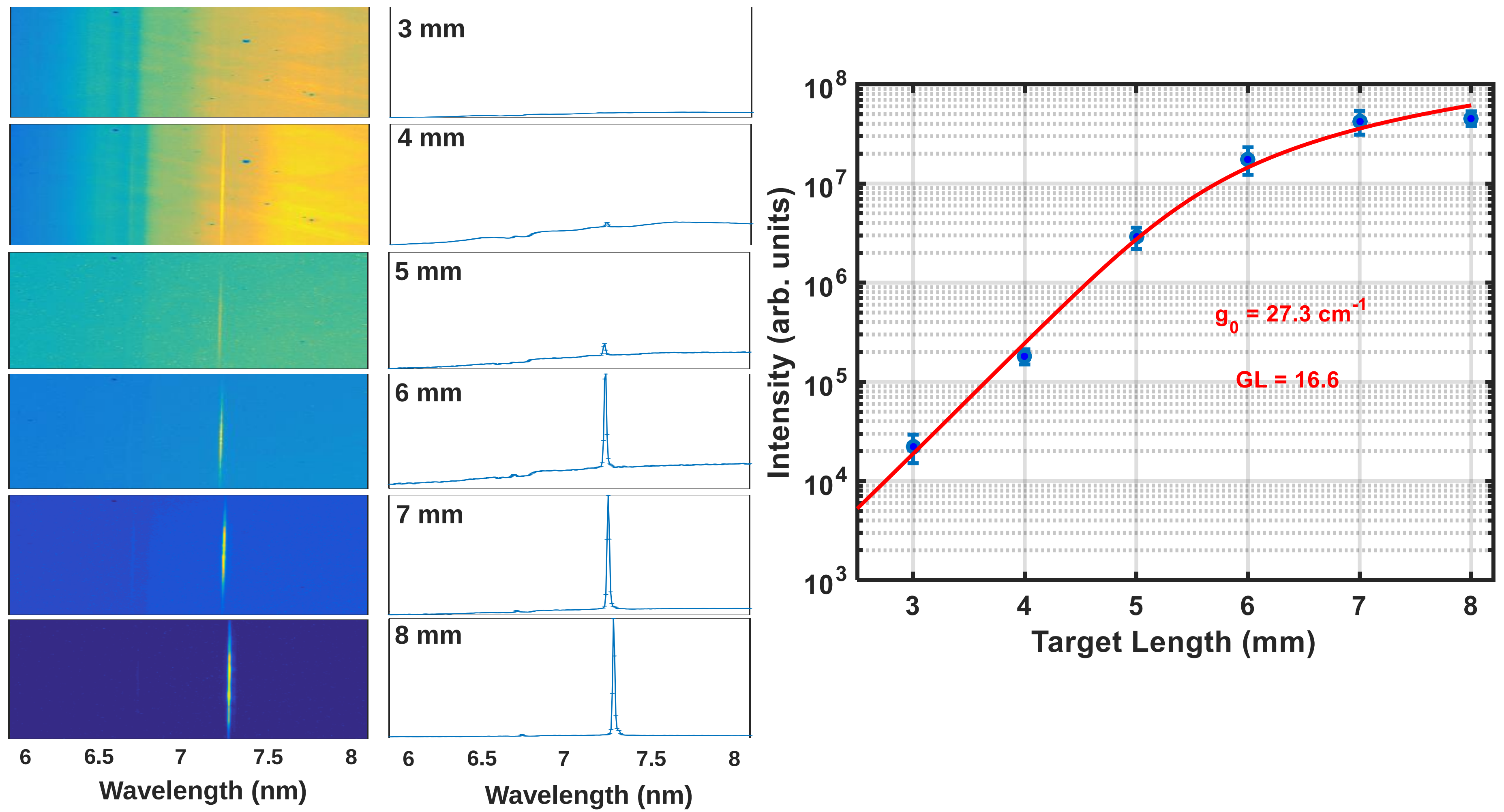
Acknowledgements



Andrew Duffin (Pacific Northwest Laboratory)
Elliot Bernstein (CSU Chemistry Department)
Zone plates: Weilun Chao, Patrick Naulleau (Lawrence Berkeley National Laboratory)

Funding: National Science Foundation and US Department

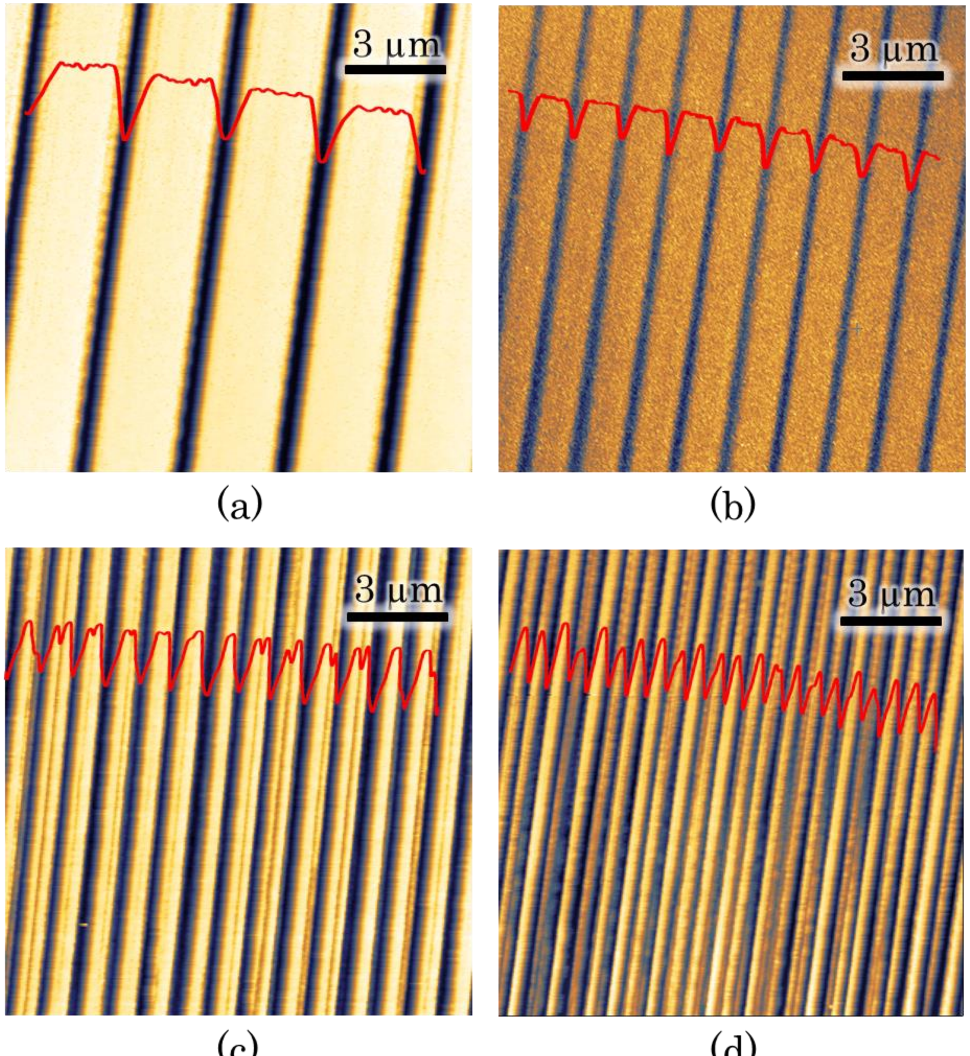
Demonstration of gain saturation in the 7.3 nm line of Ni-like Sm



Energy on target = 11.4 J , pre-pulse width= 185 ps, short pulse width= 0.7 ps , 30% pre-pulse

Frequency multiplication of periodic patterns by fractional Talbot lithography

Frequency multiplication factors up to 5X were demonstrated

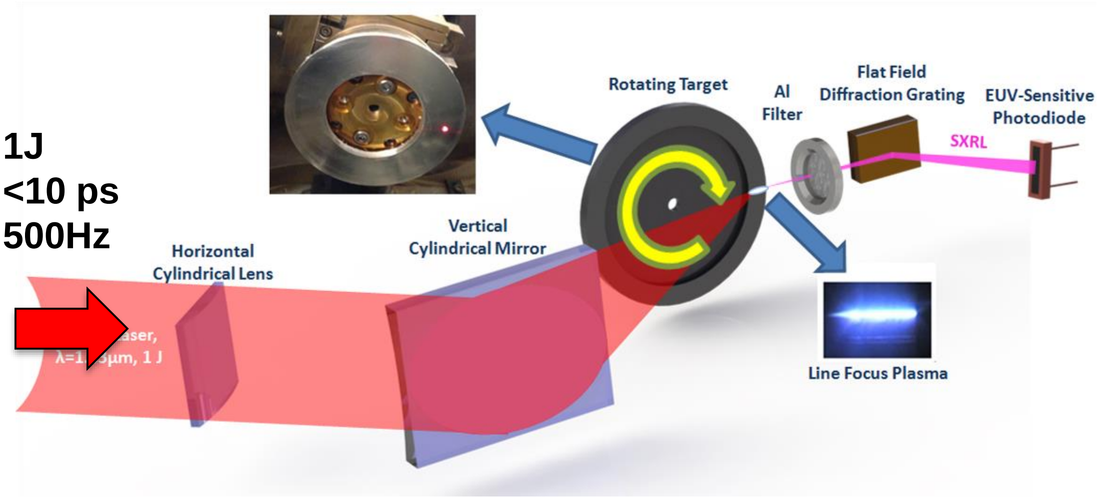


(a) (b) (c) (d)

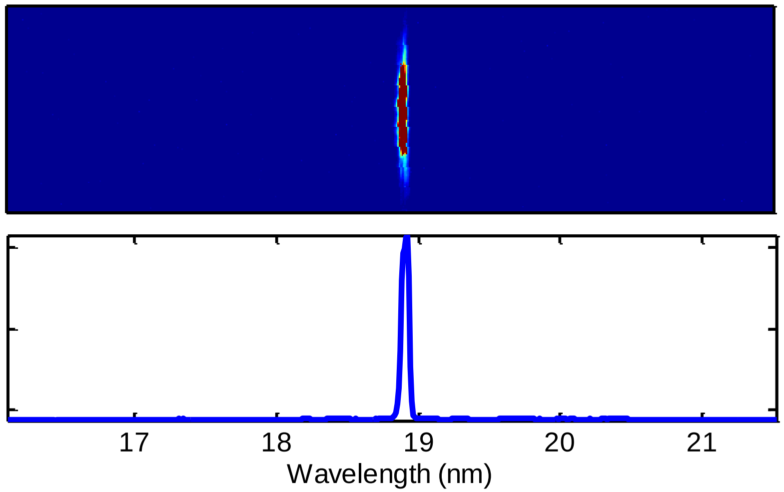
Optics Letters, Doc. ID 224904

λ = 18.9nm Laser operating at 400 Hz

1J
<10 ps
500Hz

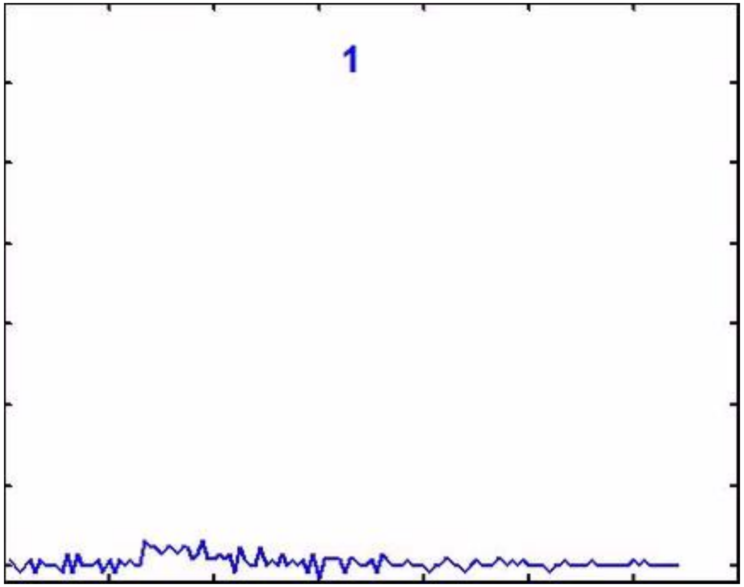


Single shot EUV spectrum showing 18.9nm Laser at 400 Hz repetition rate



400 Hz repetition rate

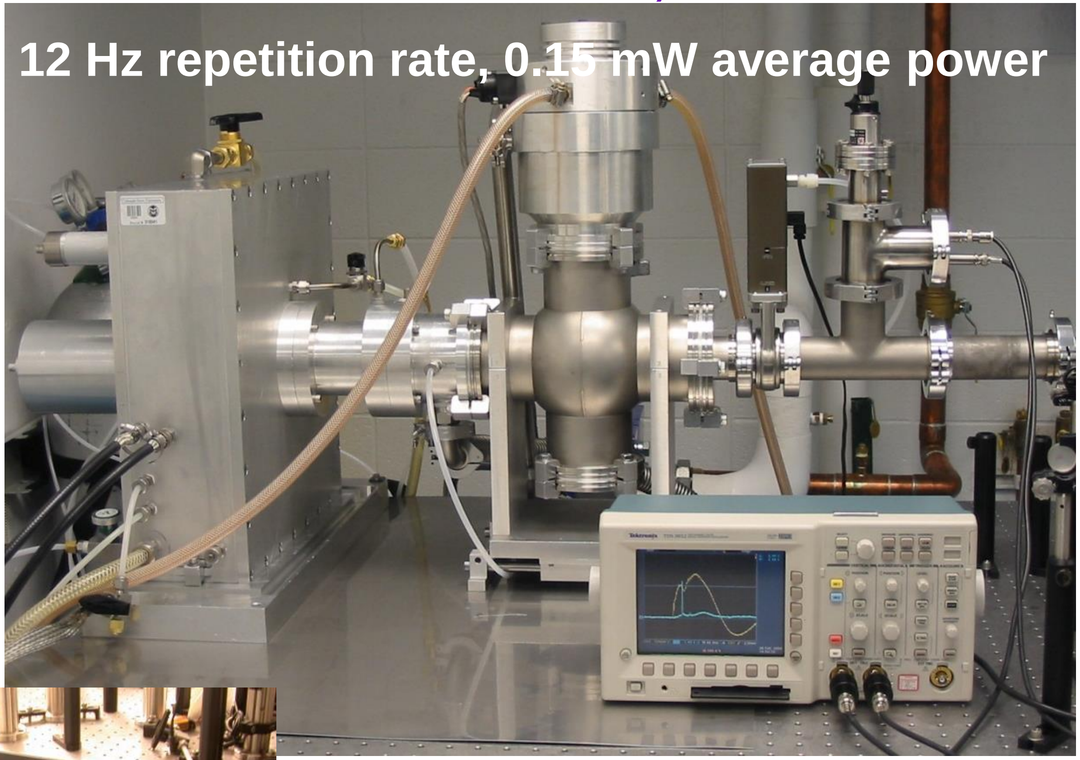
Raw EUV photodiode output of first 400 shots (1 second).



C. Baumgarten, et al., Opt. Lett. ***41*** *(2016).*

Recent research has shrunk capillary discharge SXRL to desk-top size

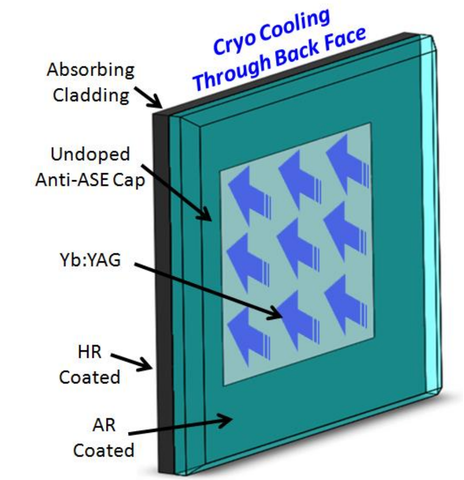
Smallest SXRL laser , λ=46.9 nm

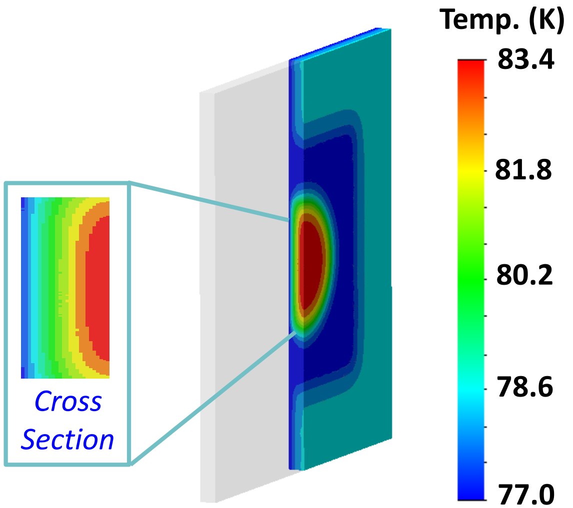


- •10 microjoule /pulse
- 0.15 mW average power
- •1-12 Hz repetition rate
- Pulse duration ~1.5 ns
- $\Delta\lambda/\lambda < 1 \times 10^{-4}$

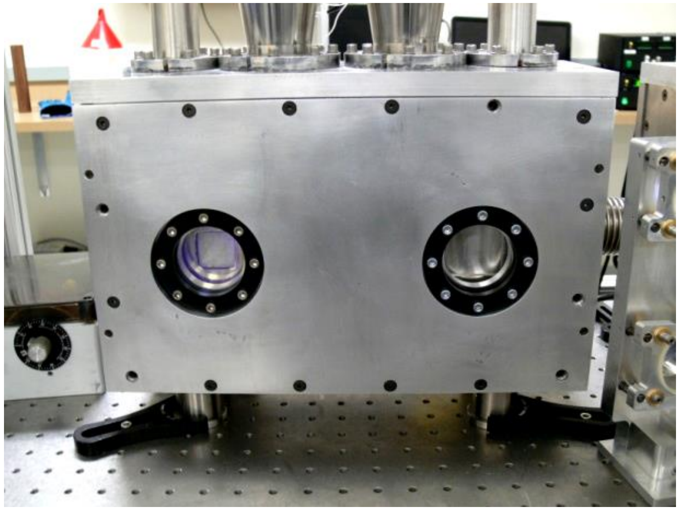
S. Heinbuch, M. Grisham, D. Martz, J.J. Rocca
Optics Express, 30,2095, (2005)

ASE-Mitigated, Thick Disk Active Mirrors





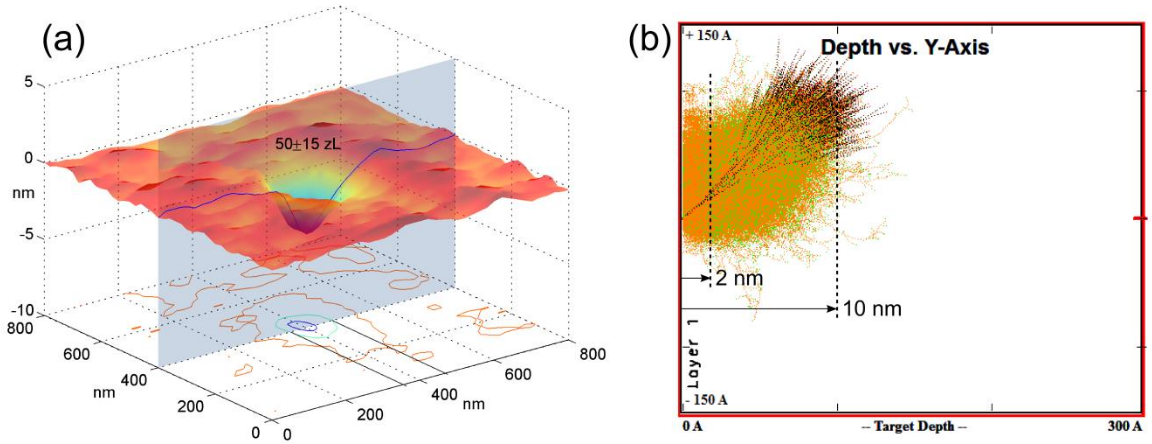
Thermally-efficient, ASE-Mitigated, Composite Yb:YAG Disk Amplifiers



Dual Disk Amplifier Heads: *Modular and Scalable*

Molecular sensitivity to aminoacid Alanine of 0.01 amol is 40× that of SIMS TOF

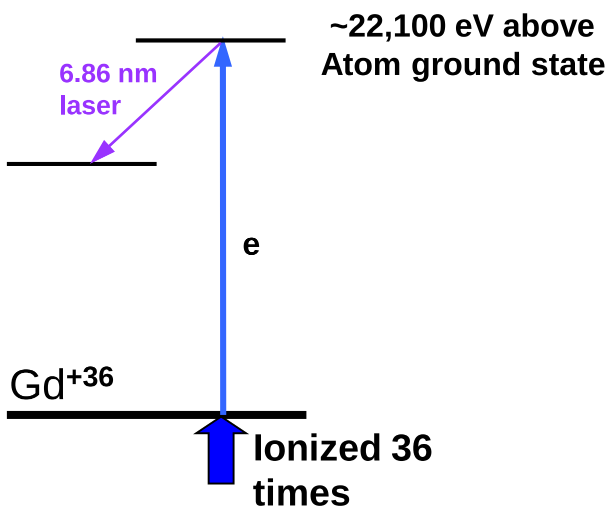
10 keV Bi^+ at 45° into C



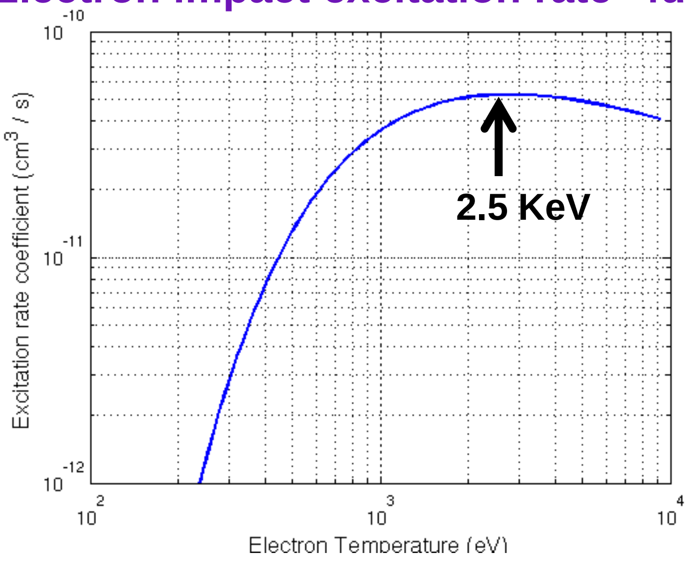
ALANINE	SXR TOF (First results)	SIMS TOF
Area probed (μm^2)	$4.5\ 10^{-2}$	$2.25\ 10^{4}$
Depth probed (μm)	$3.5\ 10^{-3}$	$2\ 10^{-3}$
Volume probed (aL)	0.05	$4.5\ 10^{4}$
Sensitivity (amol)	**0.01**	0.4
Ion yield, normalized to probed volume (L^{-1})	$4\ 10^{14}$	$8.5\ 10^{10}$
Level of fragmentation	1.1	1

I. Kuznetsov et al, Nature Communications, ***6****, 6944, (2015)*

Electron impact excitation of 6.86 nm Gd laser requires plasma with high electron temperature

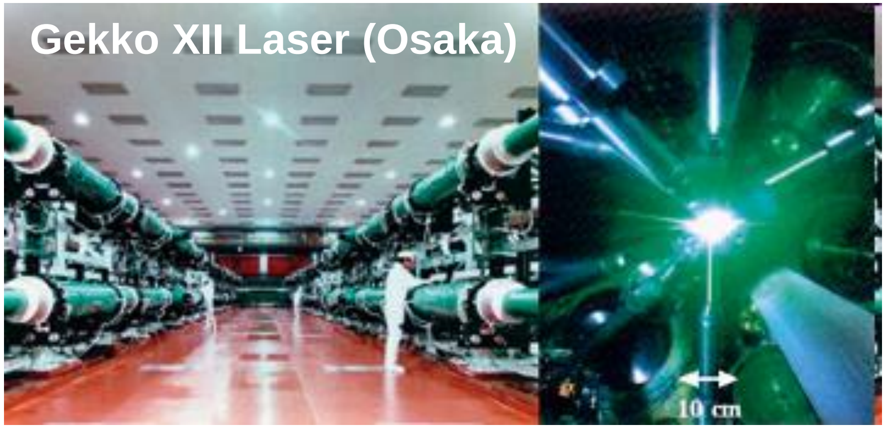


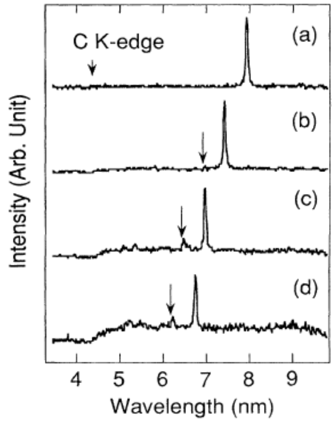
Electron impact excitation rate 4d $^1S_0$

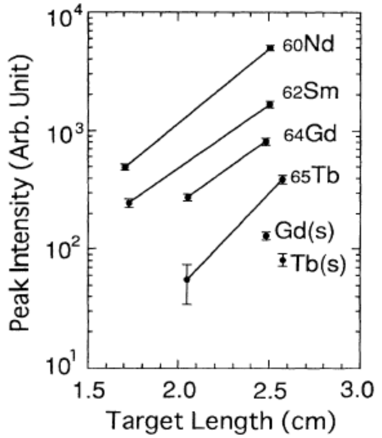


Previous work achieved unsaturated lasing at 6.86 nm in Ni-like Gd

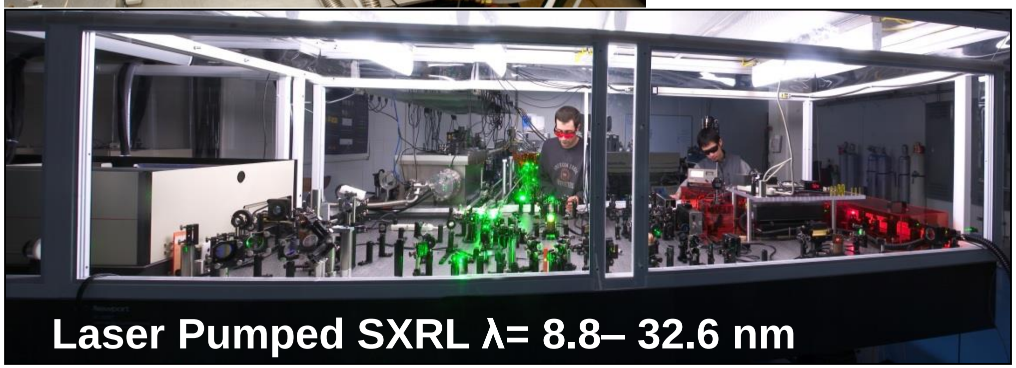
•Daido et al. using 250 J of laser pump energy (Phys. Rev. Lett. 75 1074, 1995)

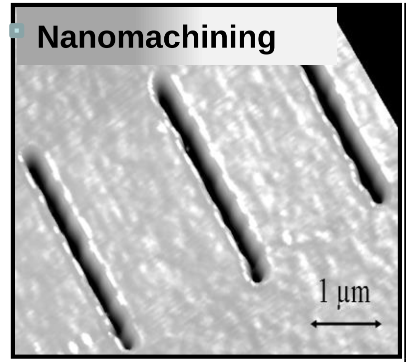


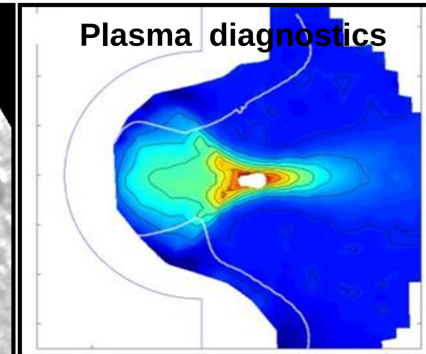


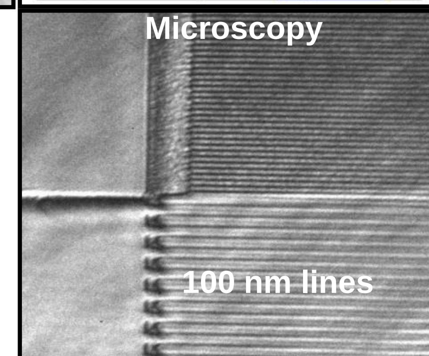


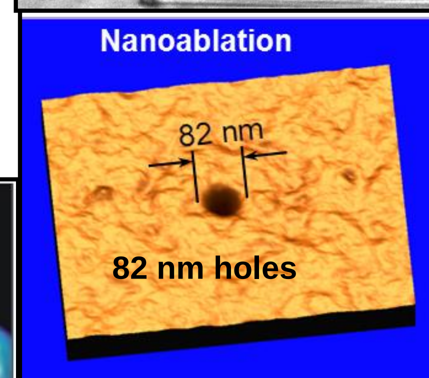
Compact plasma-based soft x-ray lasers can be installed at the application's site



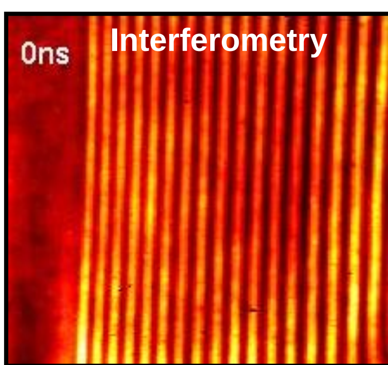


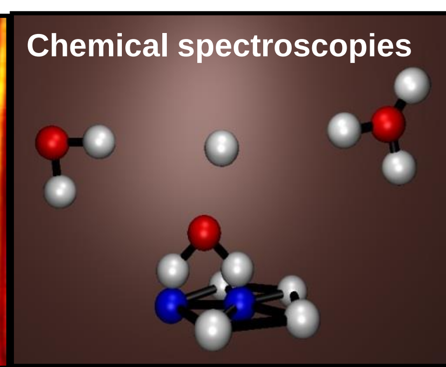


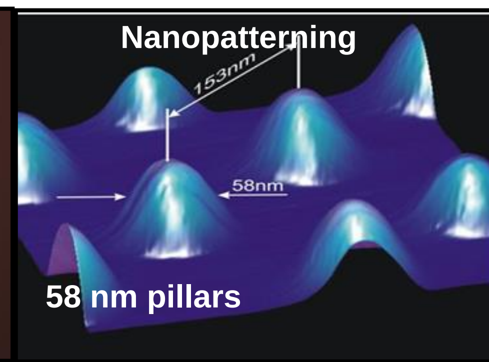




- High pulse energy (μJ-mJ)
- High monochromaticity ($\lambda/\Delta\lambda < 10^{-4}$)
- High peak spectral brightness



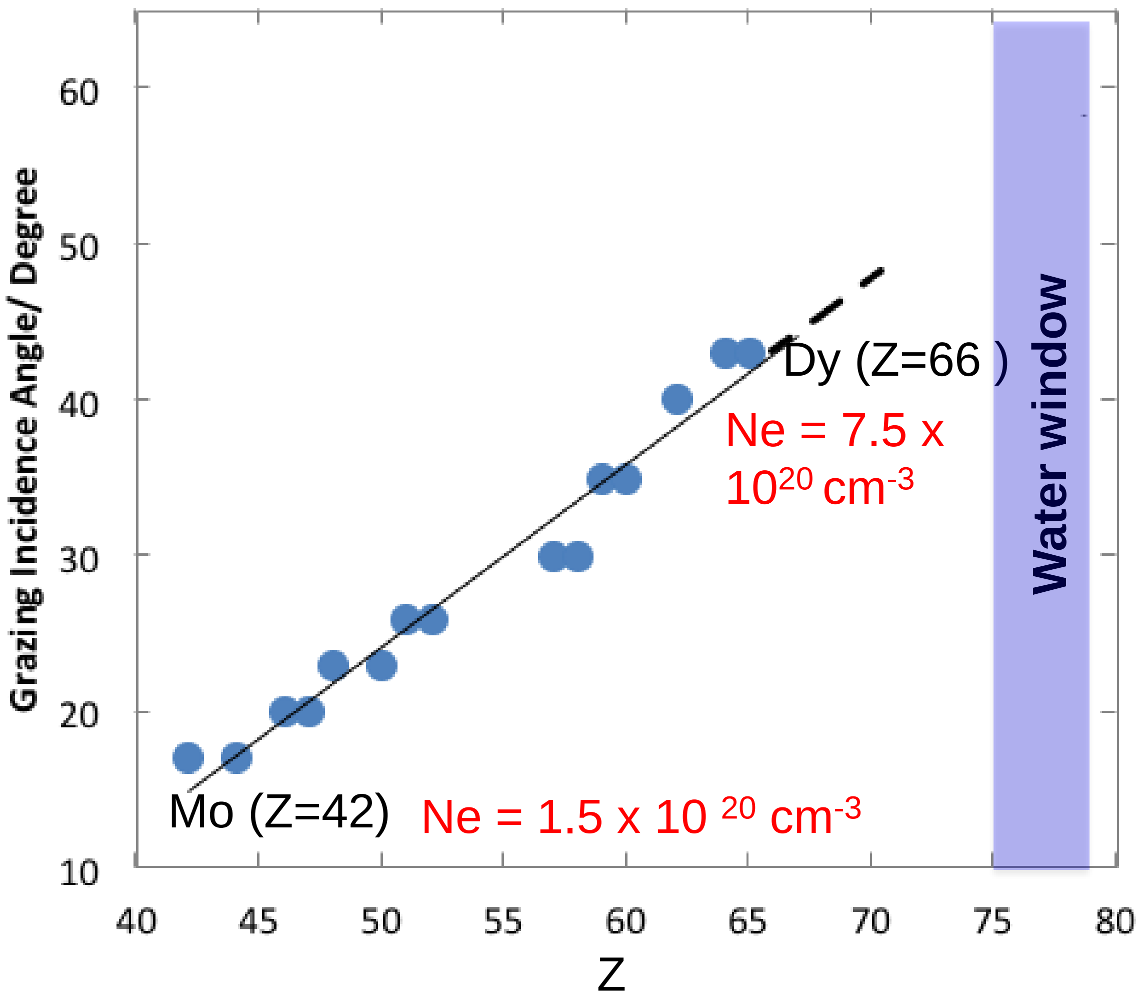


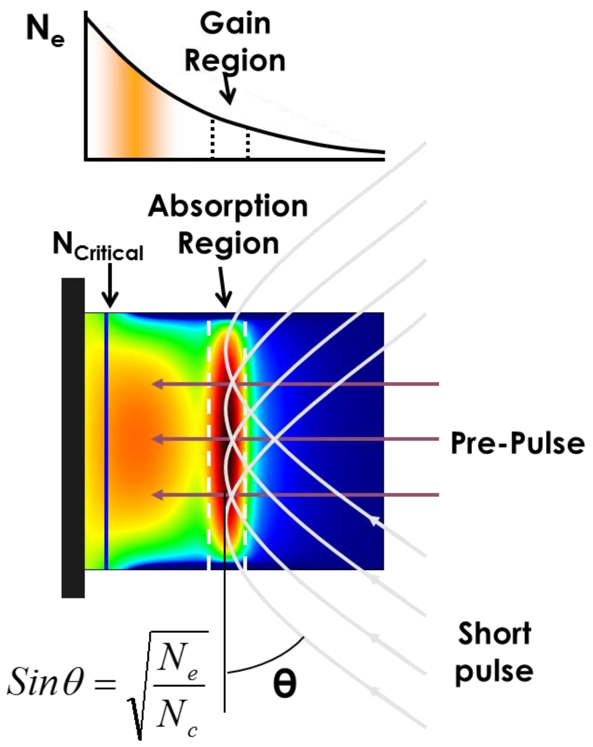


Optimum grazing incidence angle increases linearly with Z

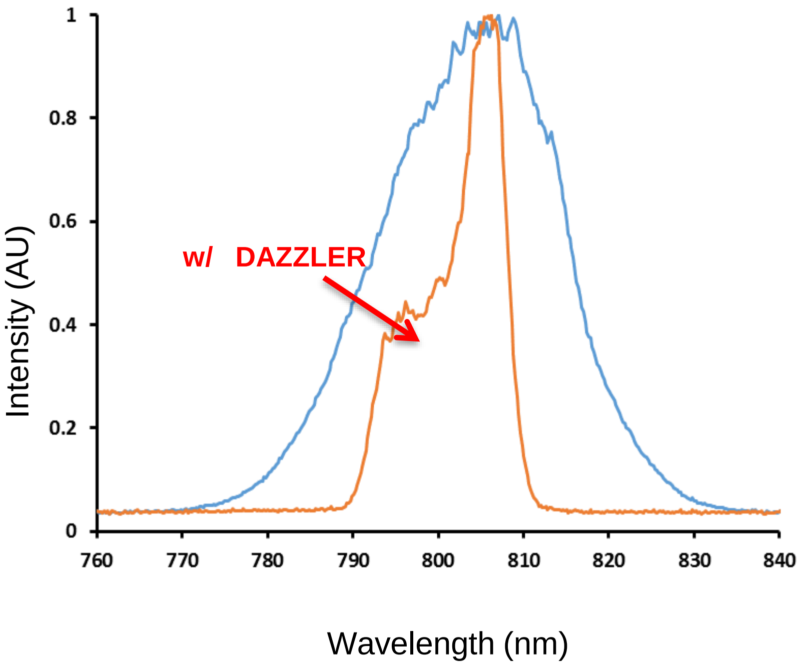
Measurement is indicative of the electron density where maximum gain occurs

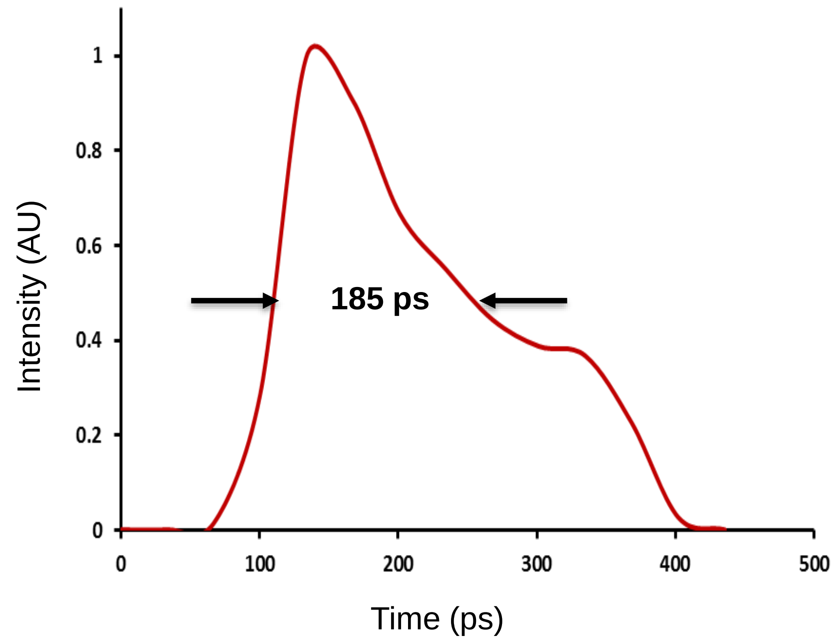
Experimentally determined optimum angles up to Dy (Z=66)

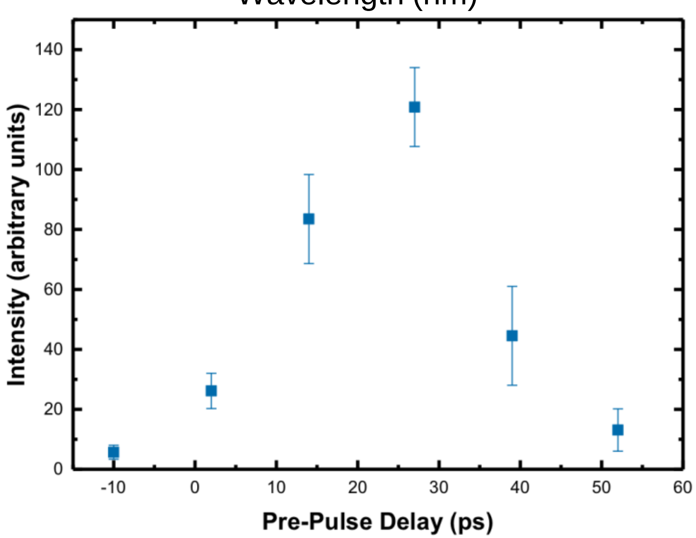


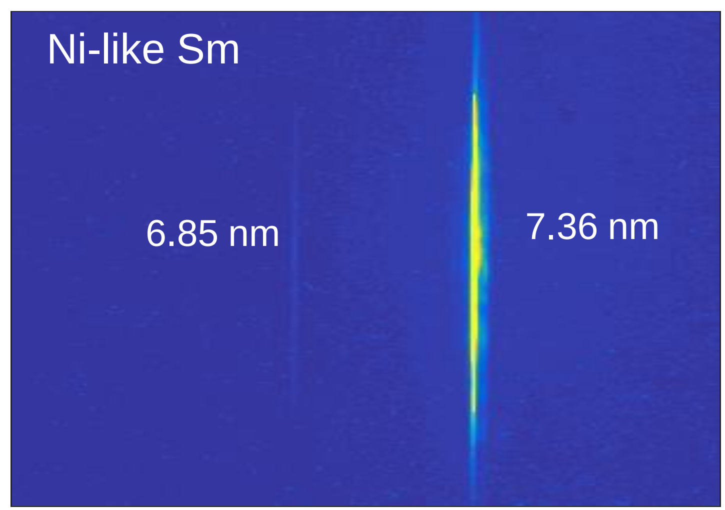


Plasma formation controlled pre-pulse duration, delay, is critical for large Sm gain



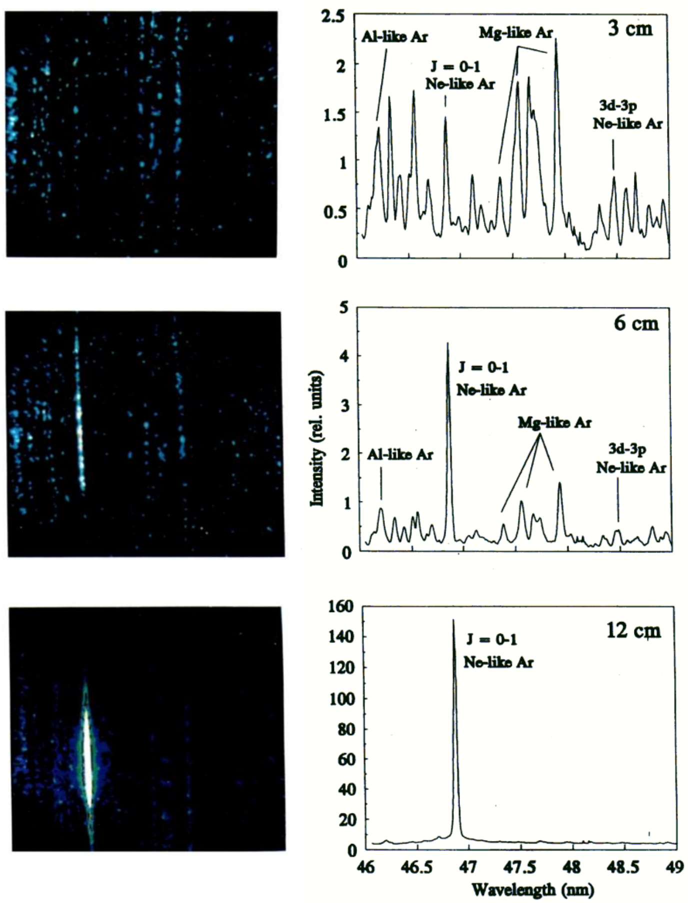


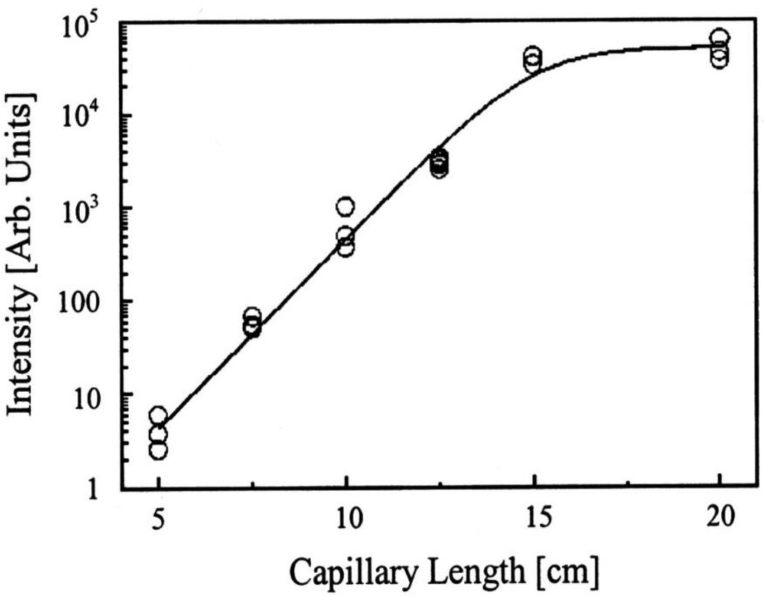




Capillary plasma columns generate gain-saturated soft X-ray amplification in Ar^{+8}

Exponential amplification in Ar^{+8} $3p^1S_0$-$3s^1P_1$ line at 46.9 nm



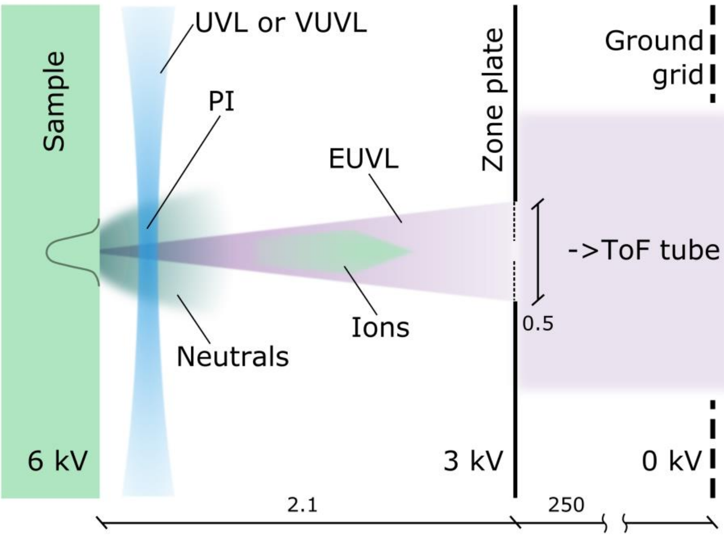


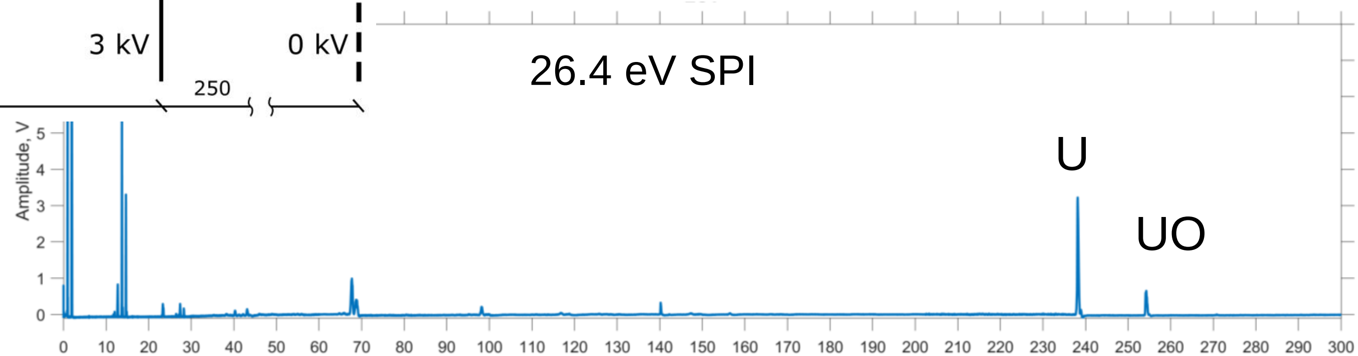
*Phys. Rev. Lett. **73** 2192 (1994)

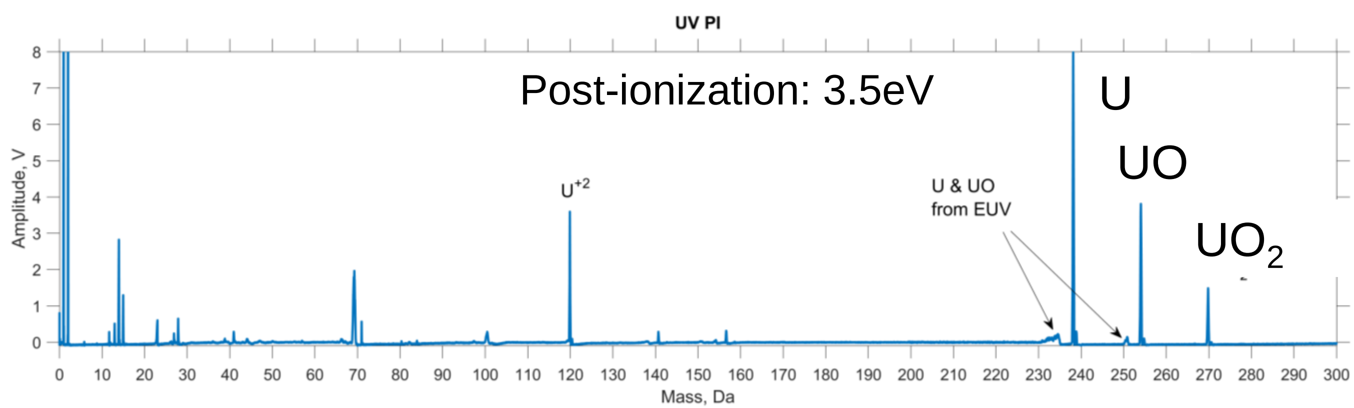
3-4 mm Capillary diameter, 25-40 kA, >30 ns rise time

Electron Temperature: 60-100 eV, Electron Density: $0.2\text{-}1.0\times10^{19}$ cm^{-3}

UV PI on Uranium (~1%) filter glass shows higher SUE

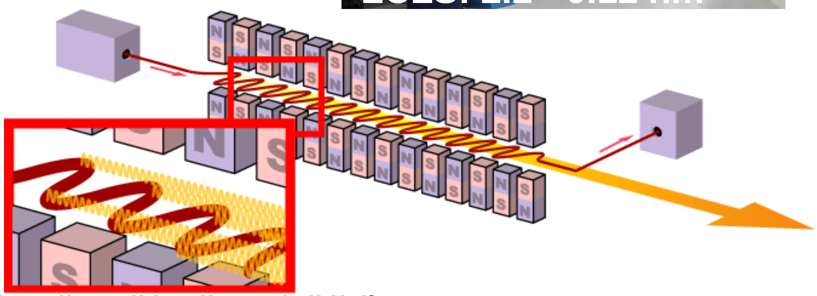




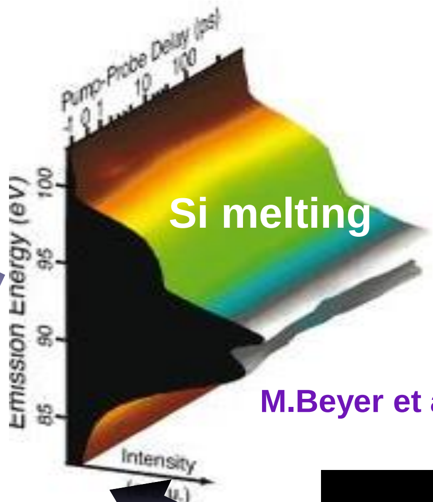


- 6.19 eV – 1st ionization potential of U

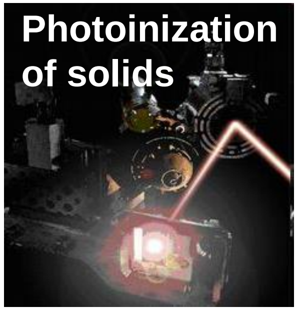
High interest in intense Coherent SXR light



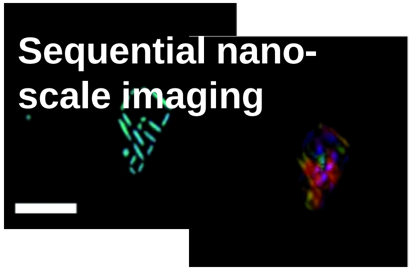
http://en.wikipedia.org/wiki/File:FEL.png



M.Beyer et al. PNAC, (2010)

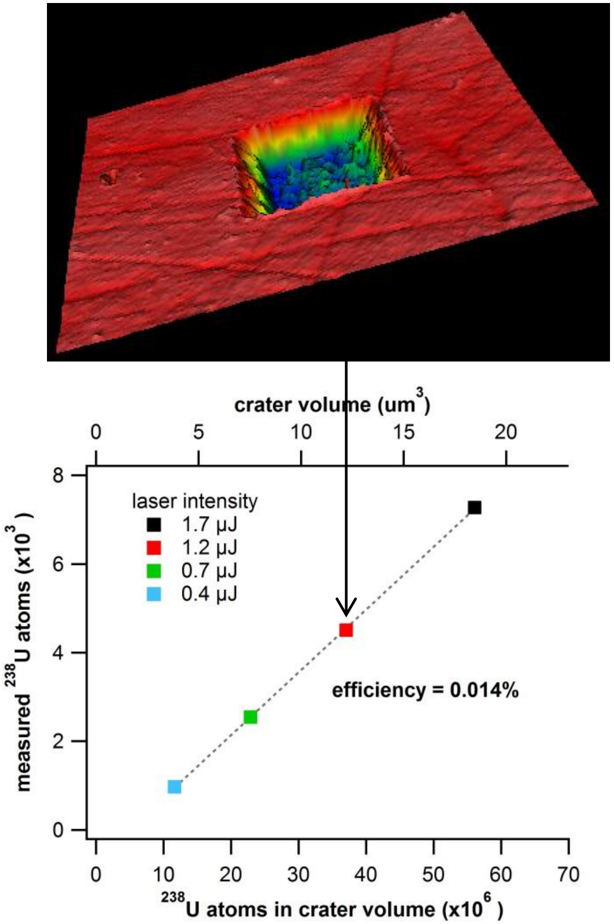


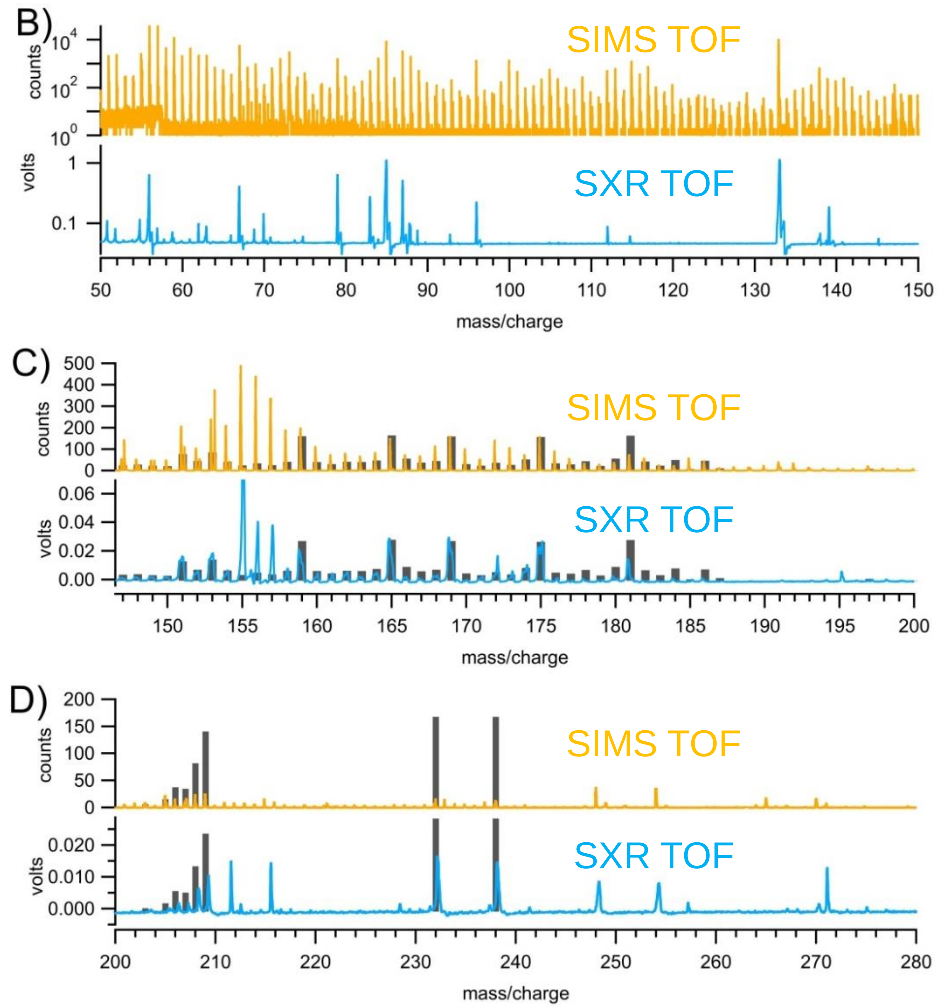
Nagler et al. Nat. Phys. (2011)



A. Barty et al. Nat. Phot., (2008)

0.014% sample utilization efficiency (SUE) of trace elements is similar to SIMS TOF



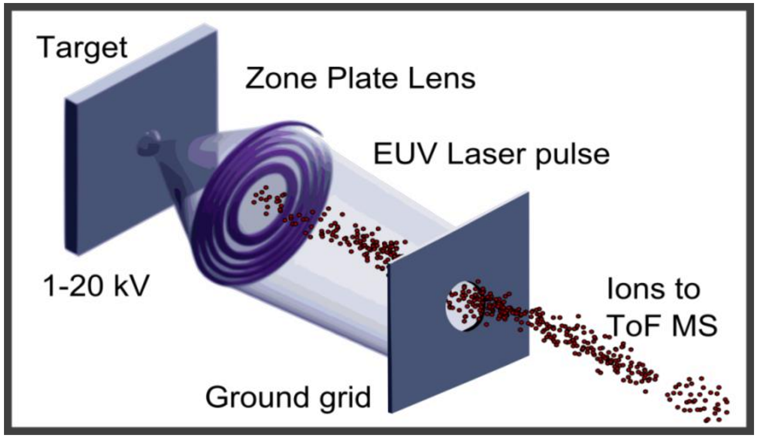


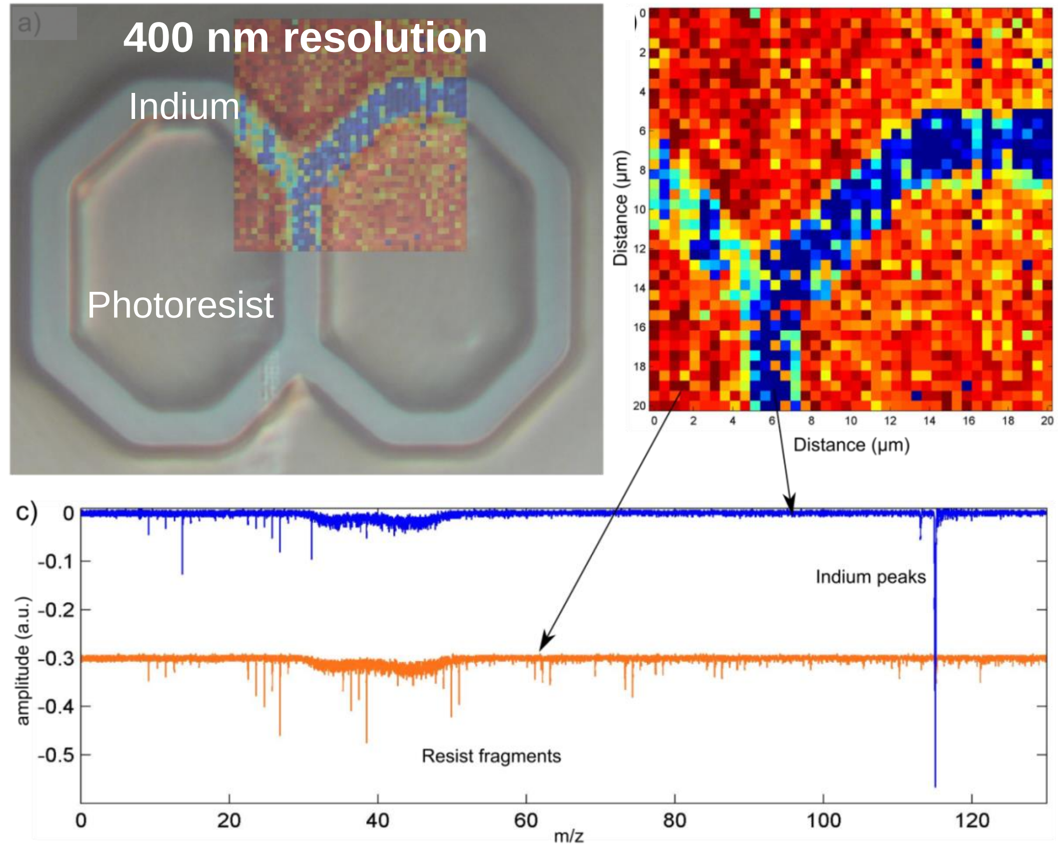
- 500 ppm of Uranium in NIST 611 glass
- 1200 shots → 10×10×0.3 µm crater

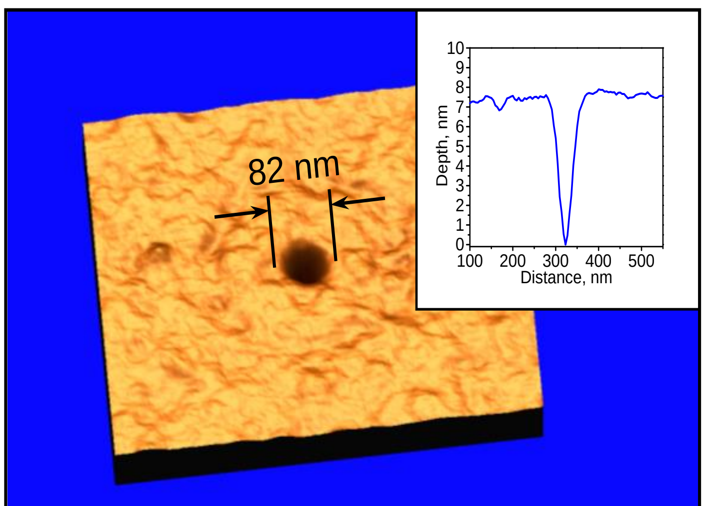
T. Green et al, J. of Analytical Atomic Spectrometry, ***32,*** *1092, (2017)*

SXRL Ablation Mass Spectrometry Imaging Nanoprobe

3-D maps of materials composition with nanometer resolution

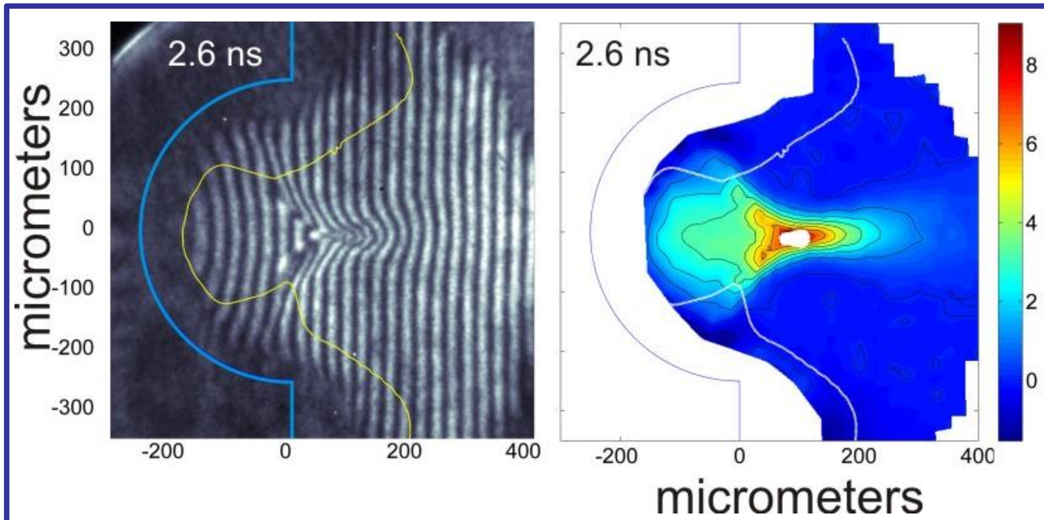






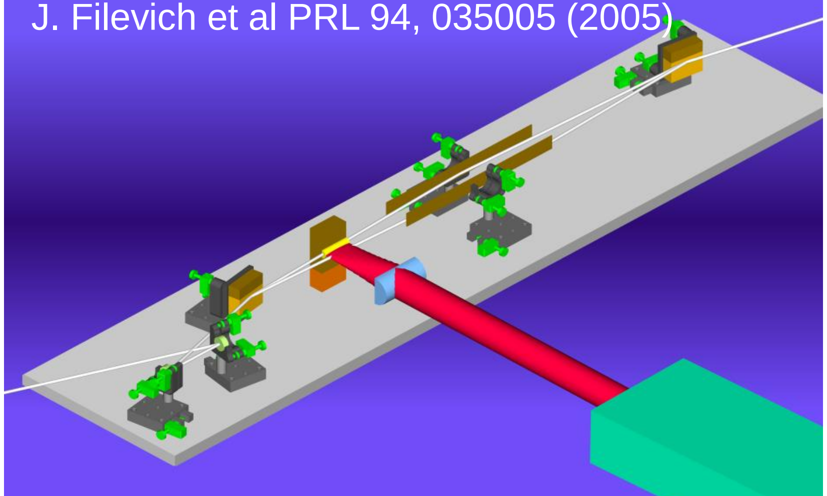
C.S. Menoni et al. **Int. Conference, on X-Ray Lasers, Paris, June (2012)**

Applications in dense plasma diagnostics and photochemistry

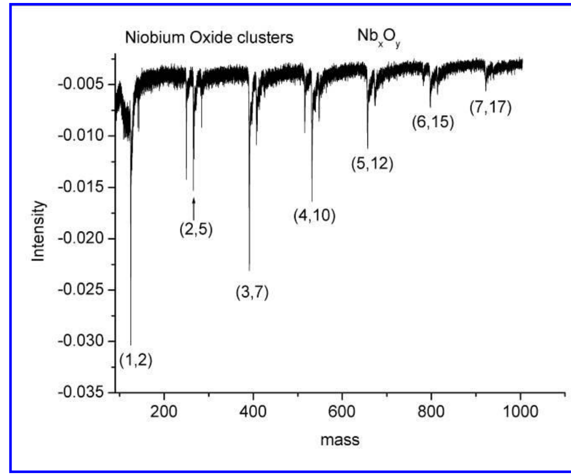


Plasma Interferometry

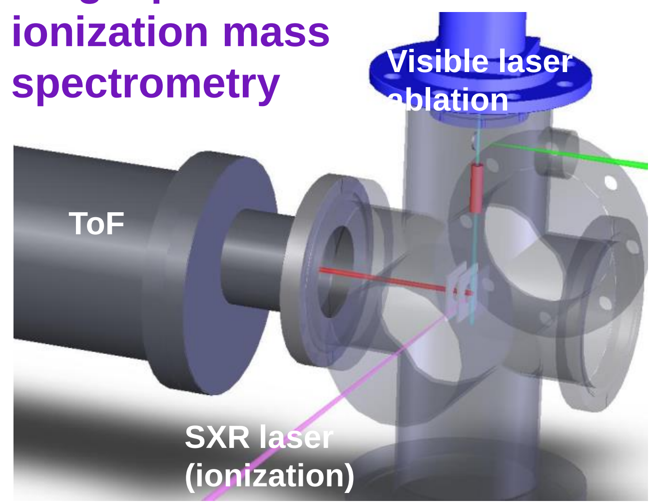
J. Filevich et al PRL 94, 035005 (2005)



*M. Purvis et al. Phys. Rev.E, **76**, (2007); **124**, (2010)*

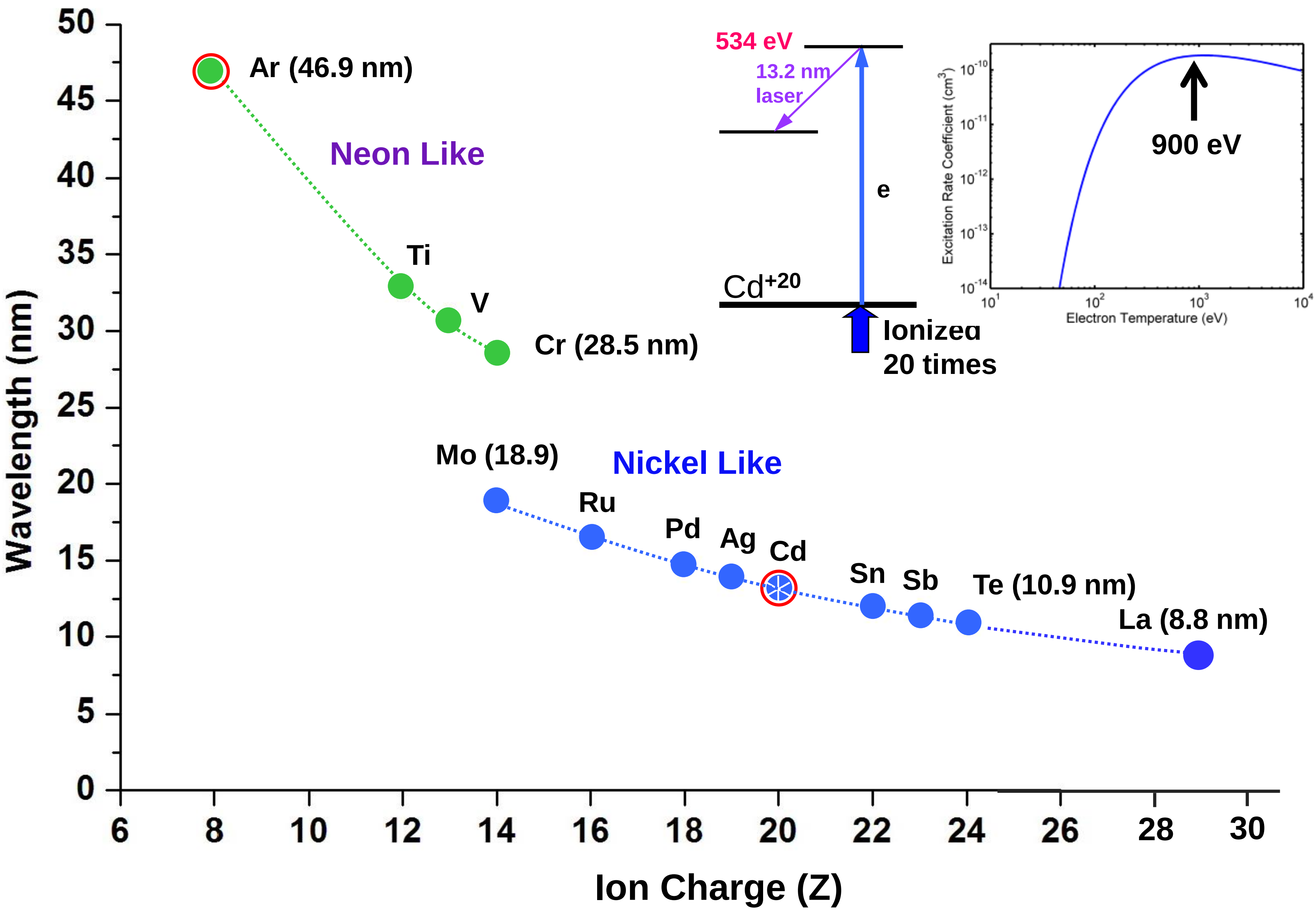


Single photon ionization mass spectrometry

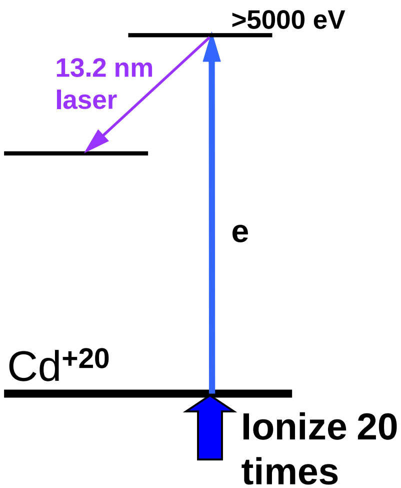


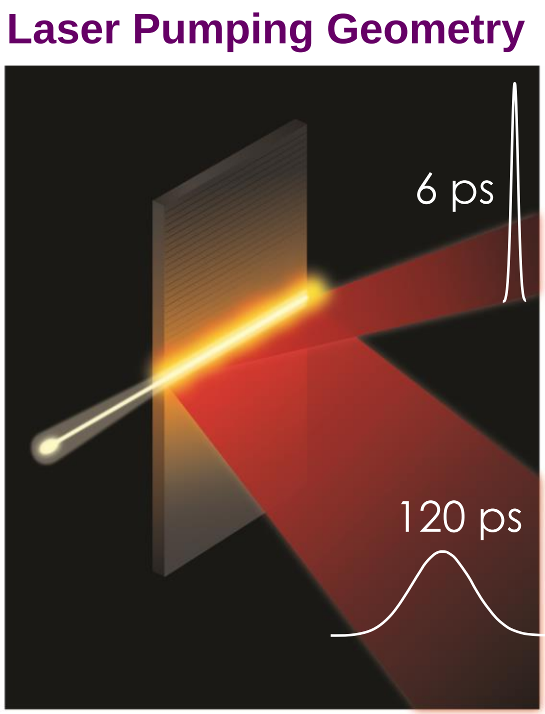
*F. Dong et al. J.Chem.Phys **124,** (2006)*
*F. Dong et al. J.Am.Chem Soc. **131**, (2009)*

Scaling to shorter wavelengths requires hotter-denser plasmas

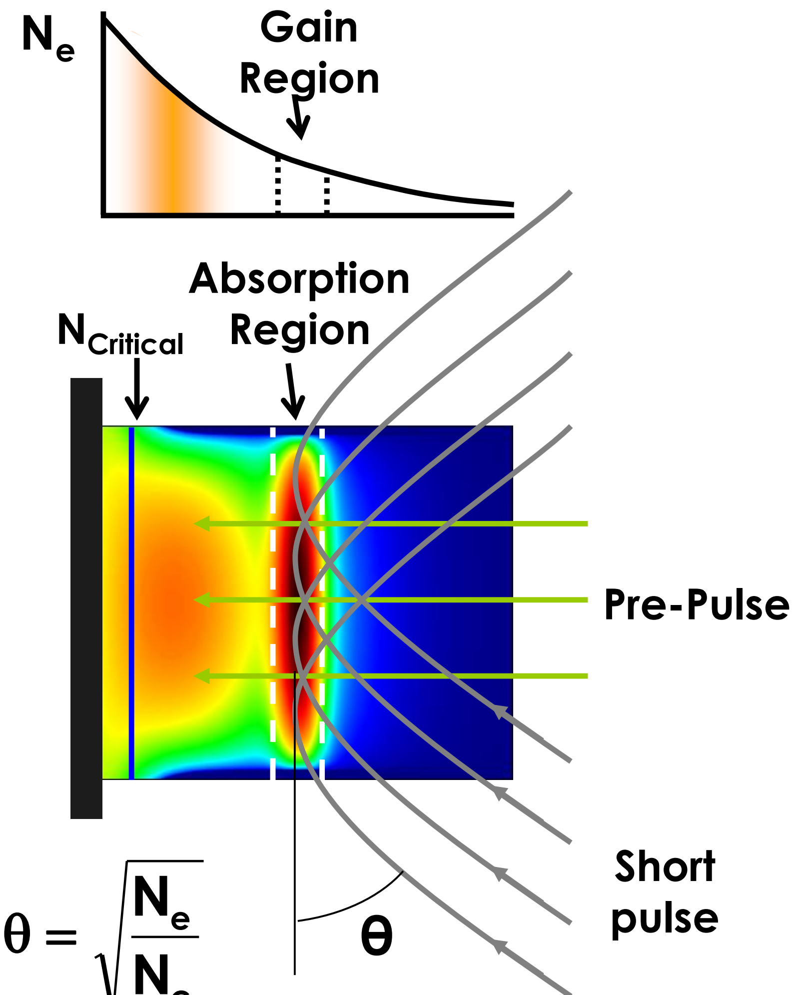


Soft X-ray lasers excited by rapid heating of plasmas with short laser pulses





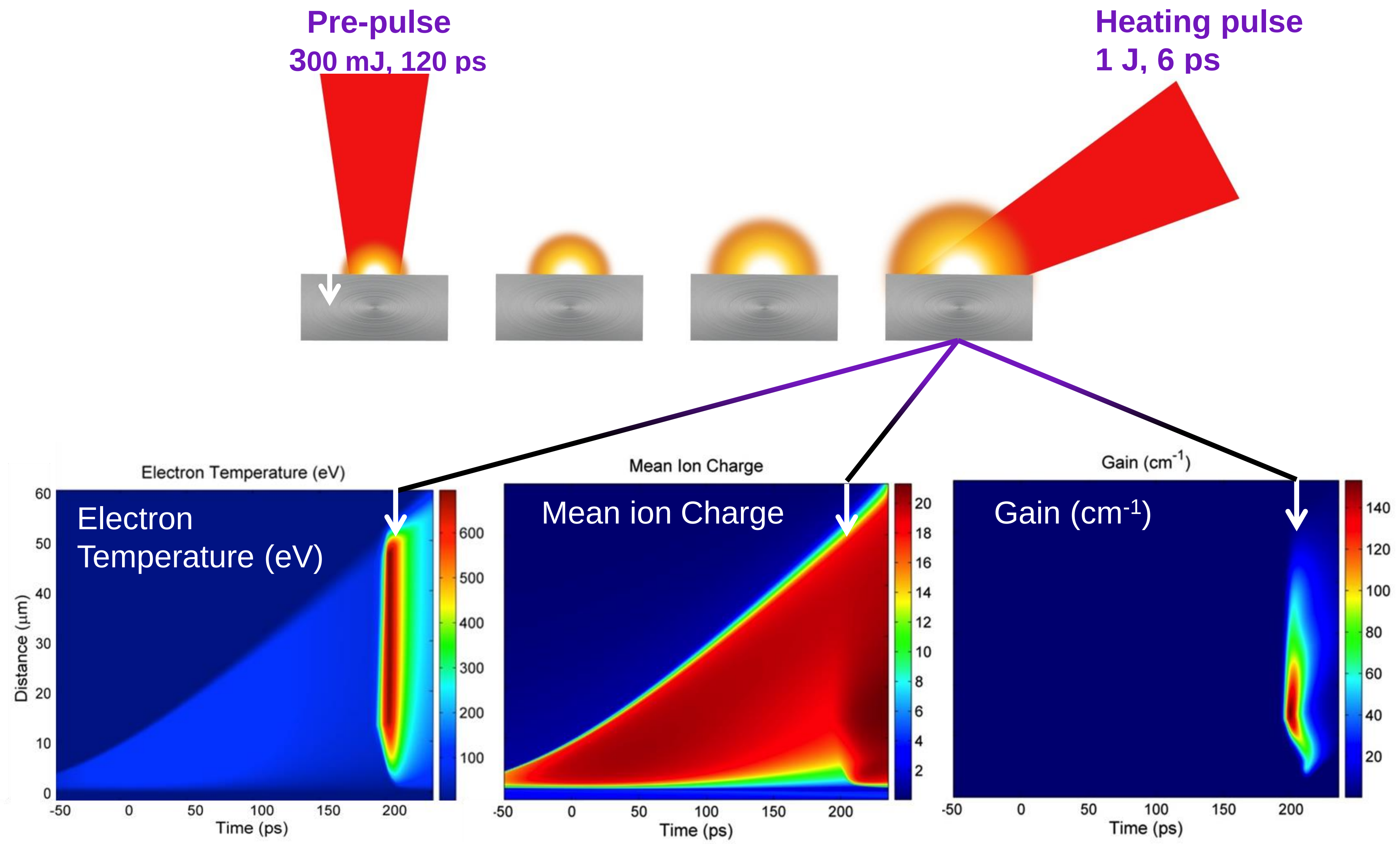
Grazing incidence allows for efficient heating of plasma region with optimum electron density



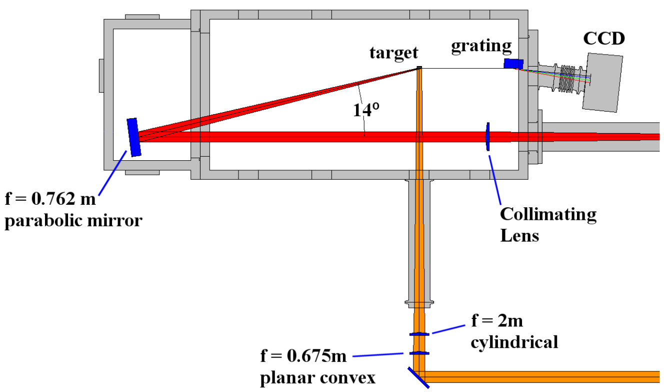
$$\theta = \sqrt{\frac{N_e}{N_c}}$$

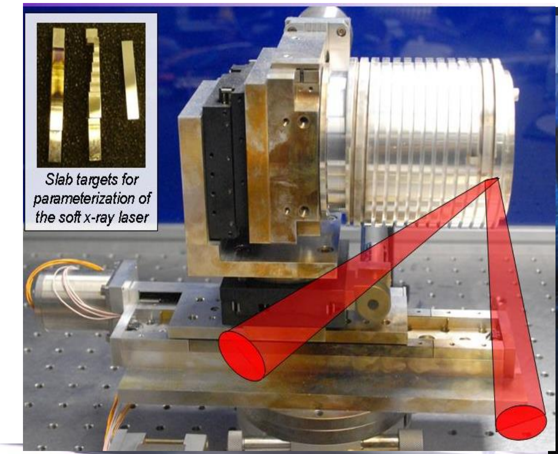
R. Keenan et al, Phys. Rev. Lett. 94, 103901 (2005) ; B.M. Luther et al, Opt. Lett. 30, 165 (2005); Transient excitation: P. Nickels, V. Shlyaptsev et al. Phys. Rev.Lett. 78,2 748, (1997)

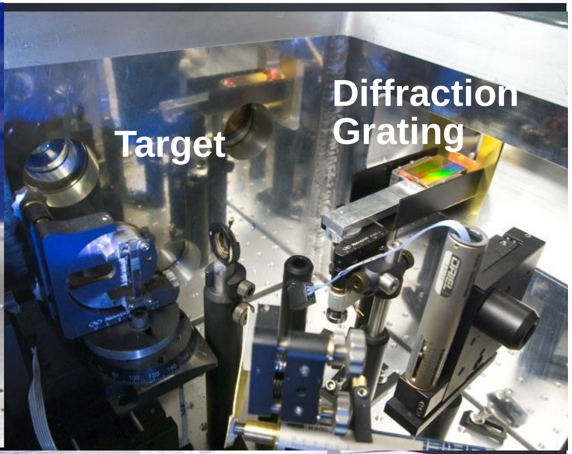
Simulation showed gain-saturated amplification at 13.2 nm in Ni-like Cd can be achieved with ~ 1 J pump

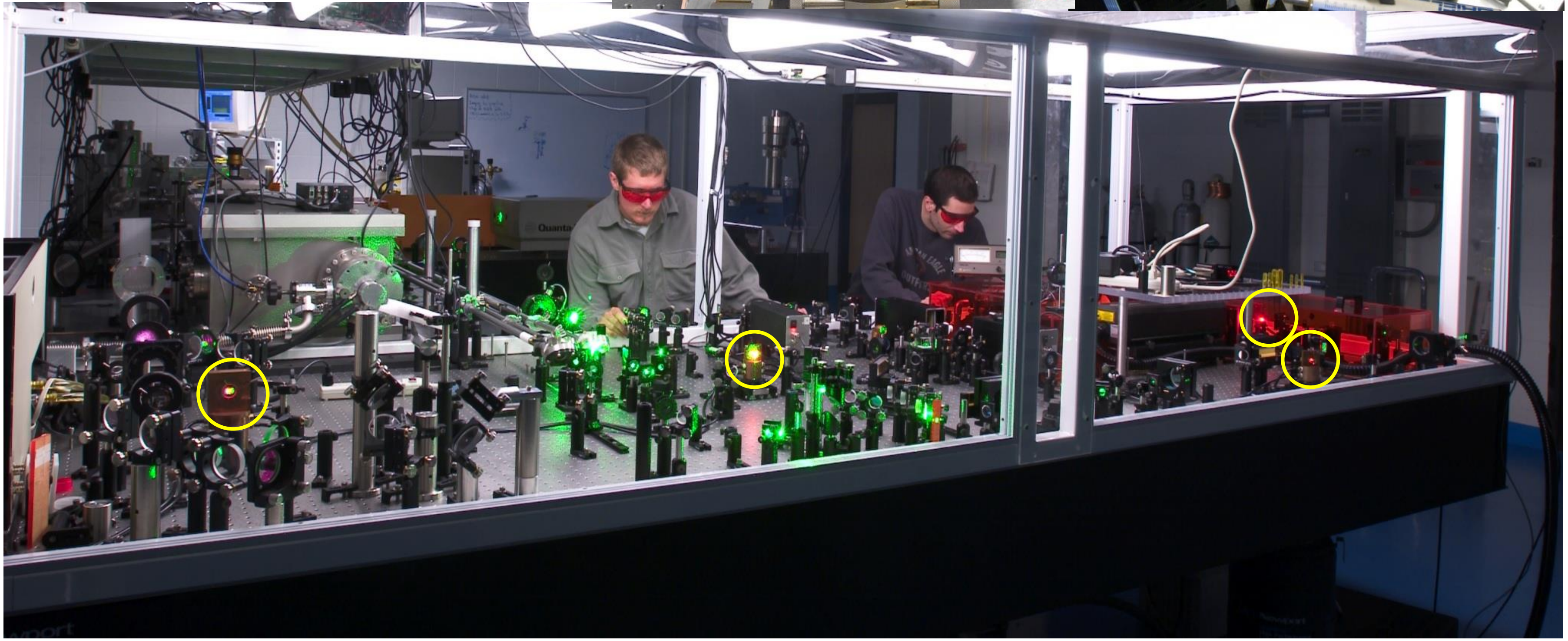


Lasers pumped by a 5-10 Hz ~ 1 J Short Pulse Table-top Ti: Sapphire System

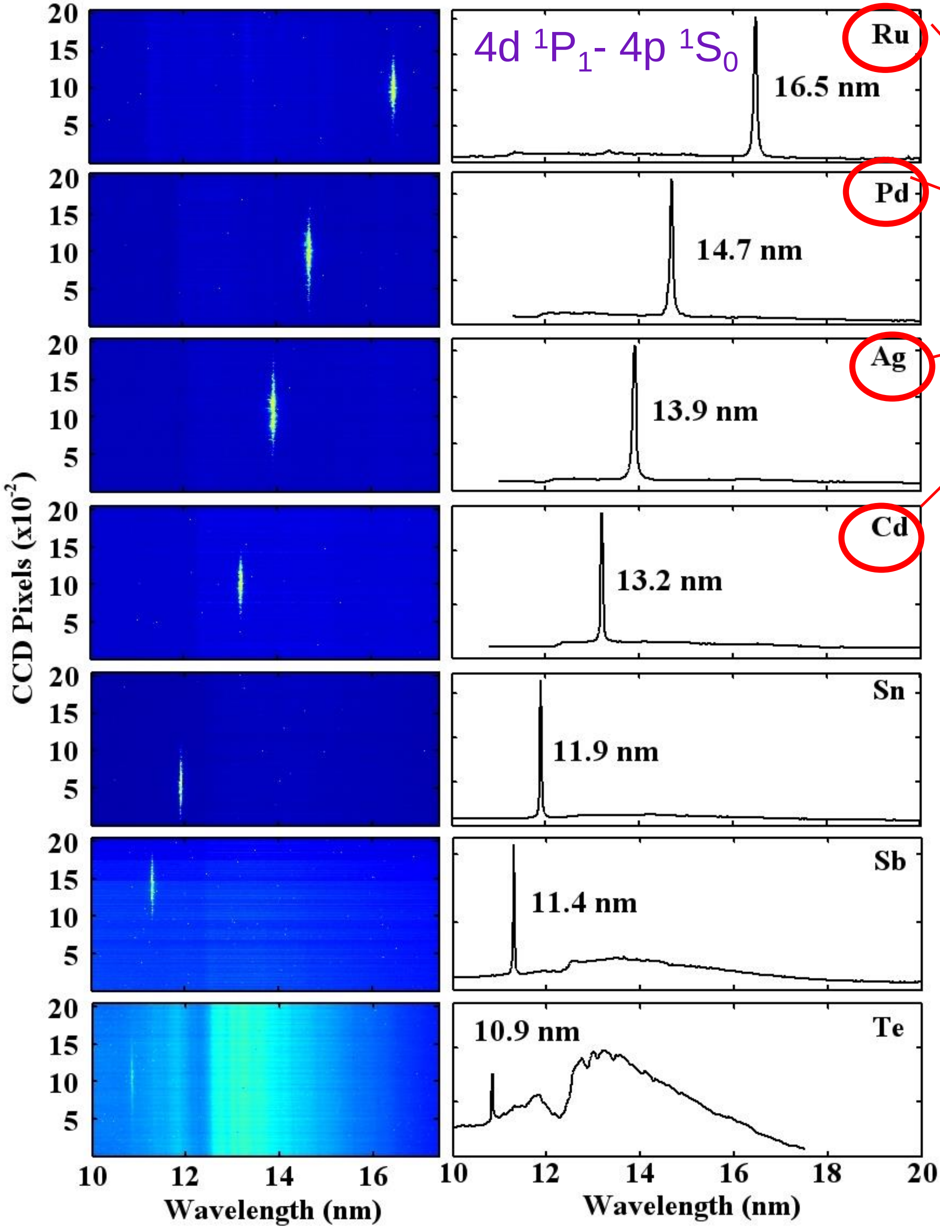




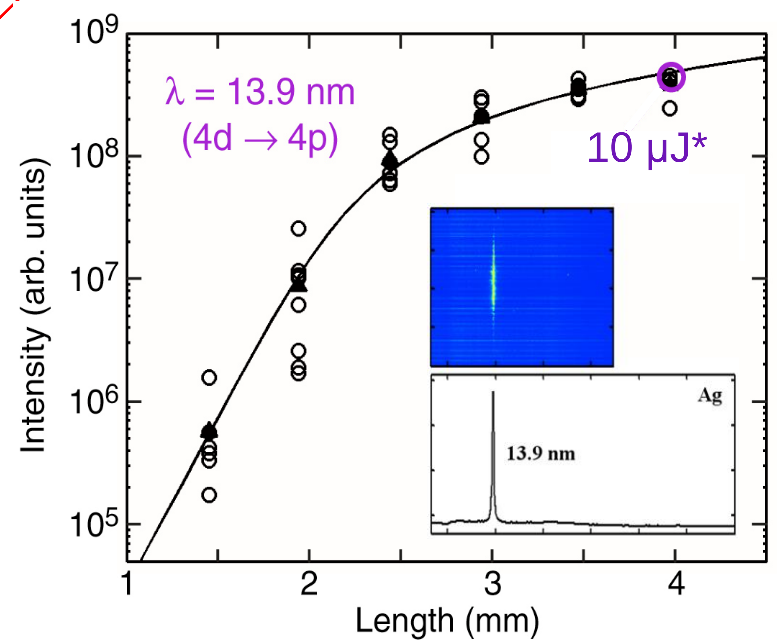




High repetition rate table-top SXRL in transitions of Ni-like ions down to 10.9 nm



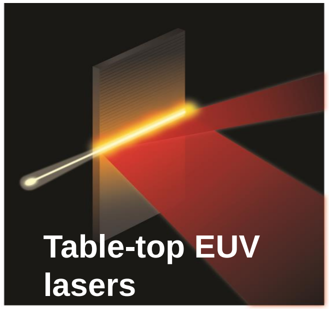
Gain saturated operation demonstrated

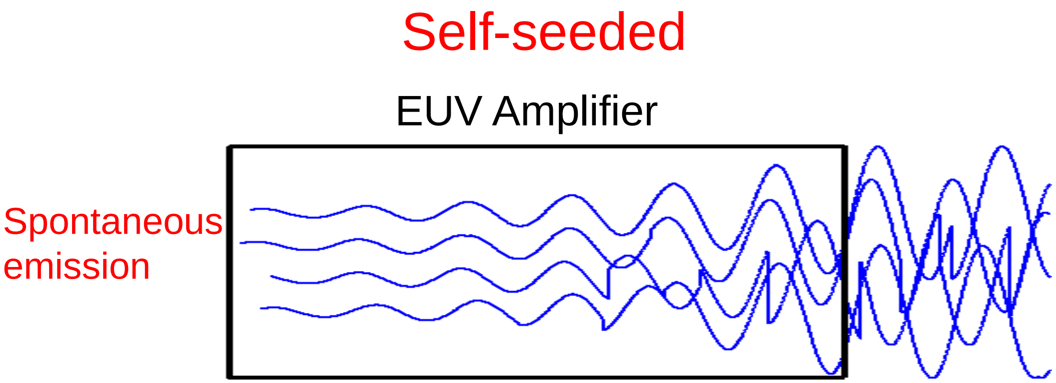


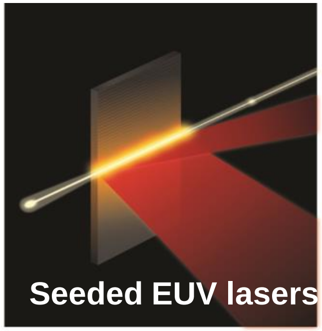
Y. Wang et al, Phys. Rev. A ***72****, 053807 (2005)*

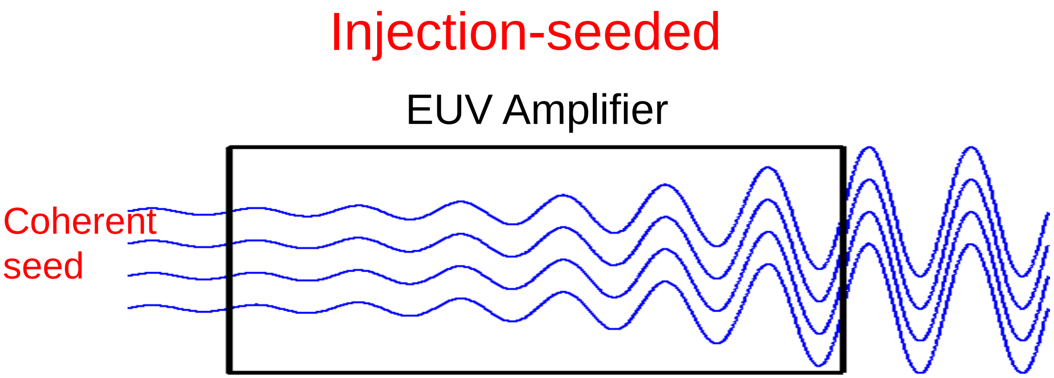
D. Martz et al. Optics Lett.* ***35**, 1632 (2010)*

SXR lasers self-seeded by spontaneous emission noise have poor temporal coherence



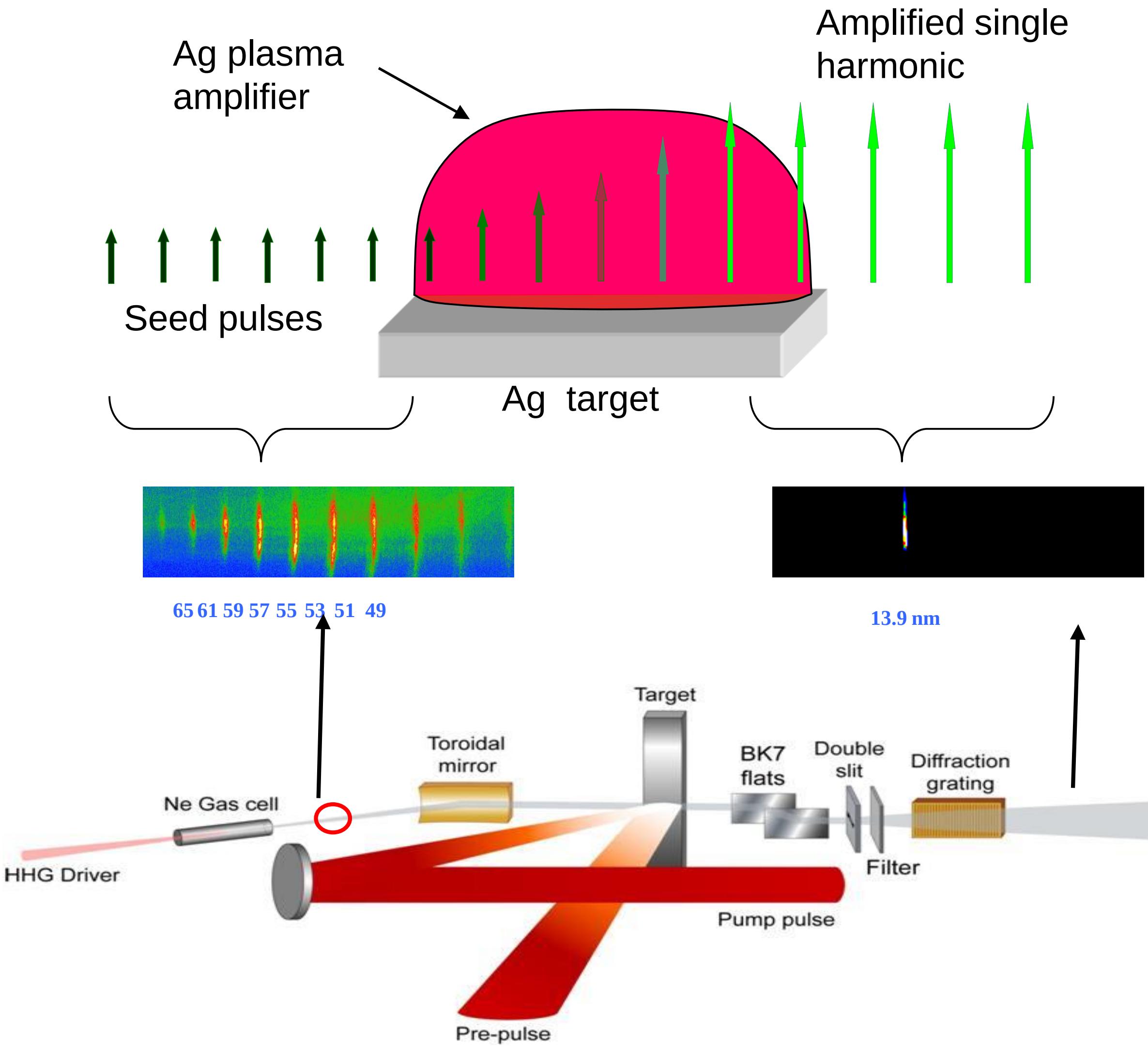




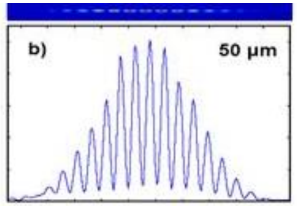


Seed pulses can be greatly amplified preserving or even improving their properties

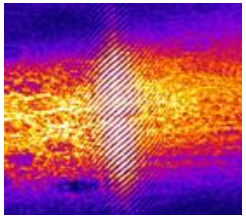
Injection-seeding SXR Lasers have full phase-coherence and shorter pulsewidth



Full spatial coherence

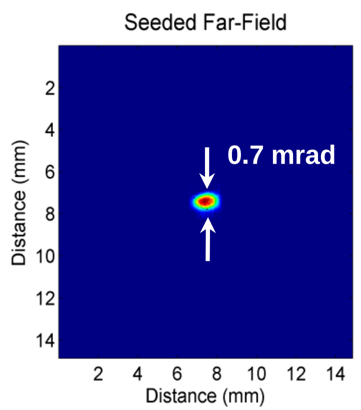


Full temporal coherence



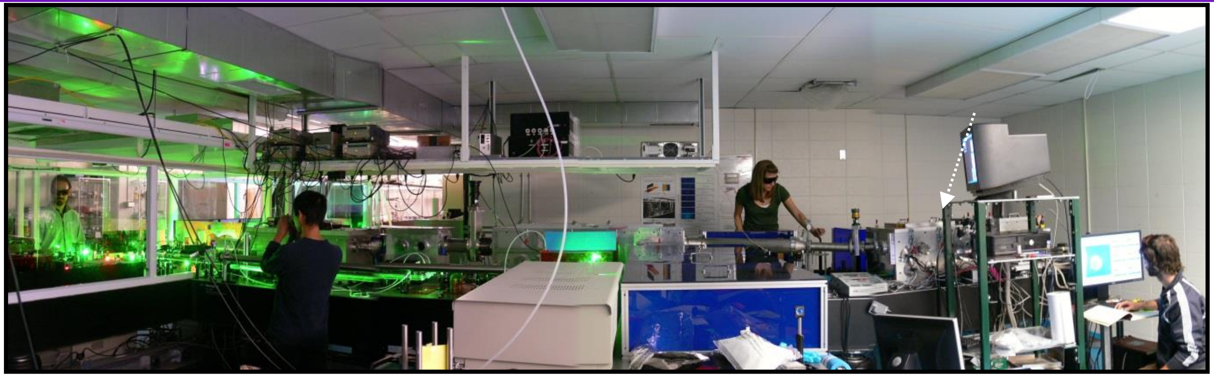
Shorter pulsewidth

(1.13±0.47)ps

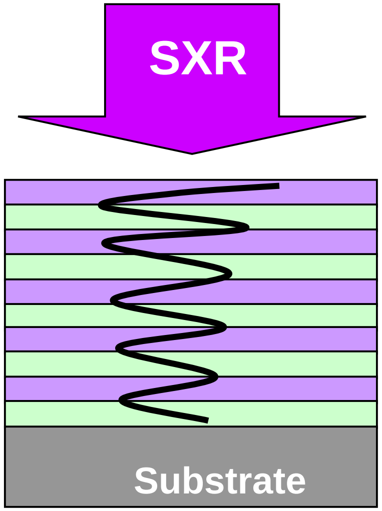


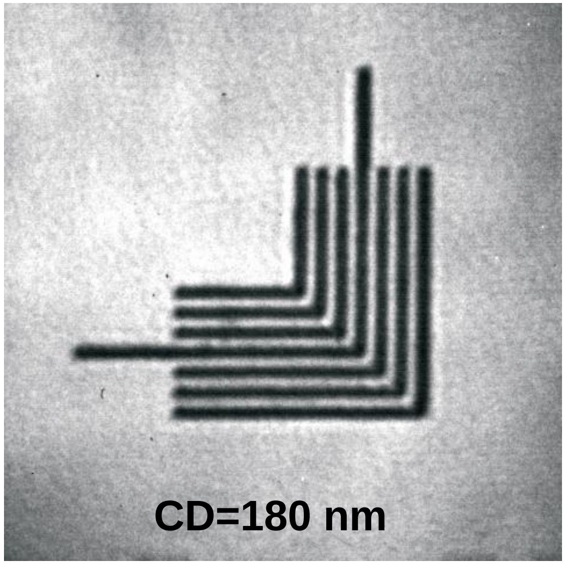
T. Ditmire et al. Phys. Rev. A. ***51****, R 4337, (1995); P. Zeitoun et al. Nature,* ***431****, 427, (2004) ;*
Y. Wang et al. Phys. Rev. Lett, ***97****, 123901 (2006) Y. Wang et al. Nature Photonics,* ***2****, 94, (2008)*

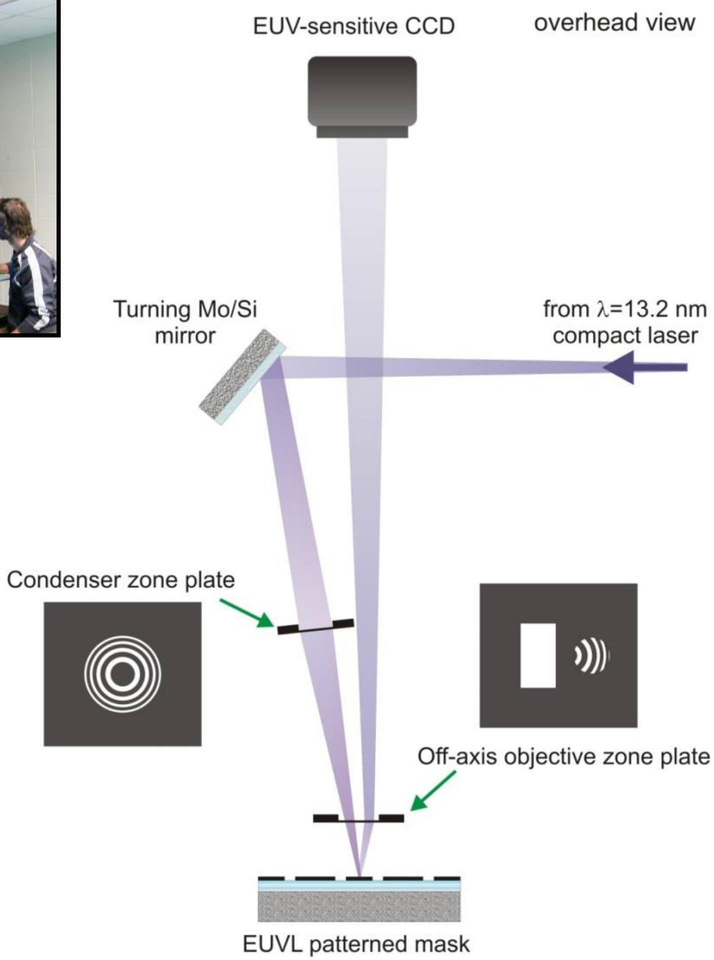
13.2 nm laser-based microscope for defect inspection in EUV lithography masks



λ= 13.2 nm resonant with Mo/Si coatings in extreme ultraviolet lithography masks



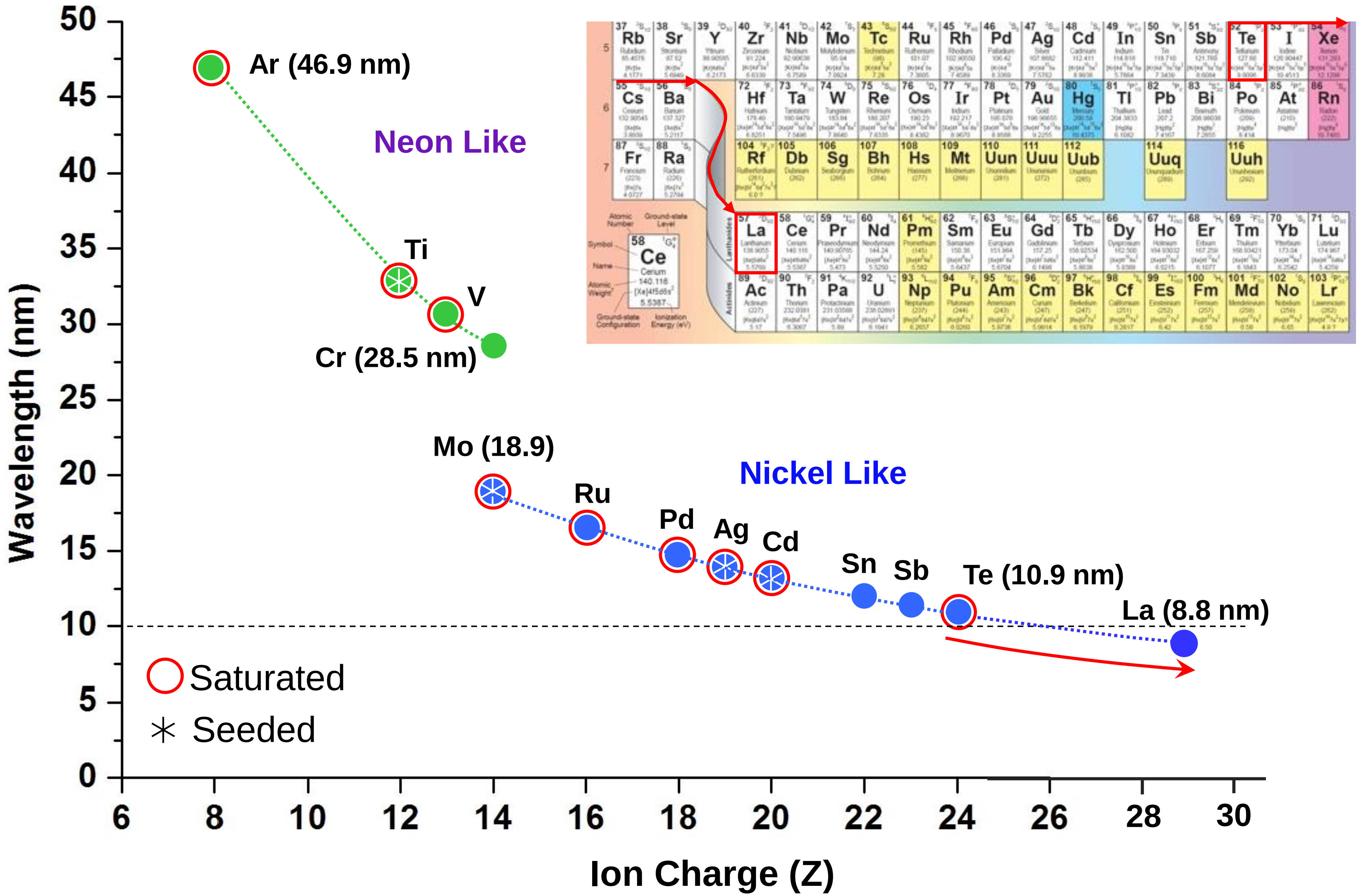




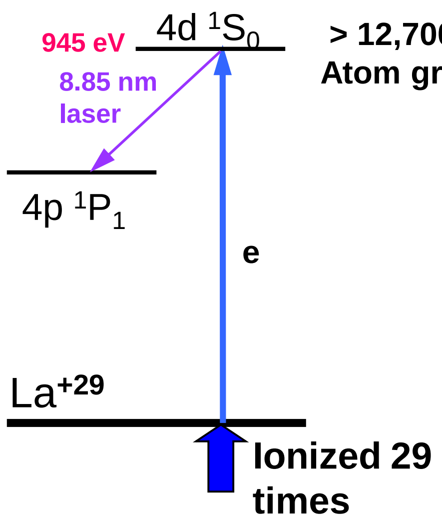
EUV Optics from CXRO, Berkeley

F. Brizuela et al., *Optics Express* ***18****, 14467, (2010)*

Extension of gain-saturated table-top SXRL to sub-10 nm wavelengths using lanthanide ions

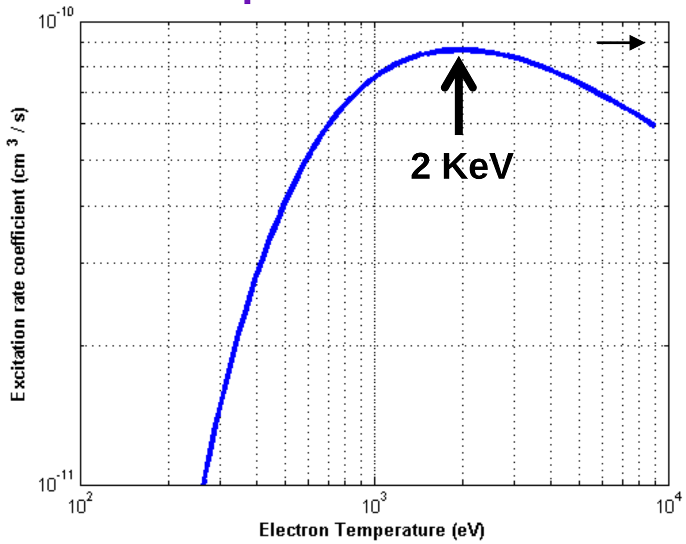


Electron impact excitation of 8.8 nm La laser requires plasma with high electron temperature



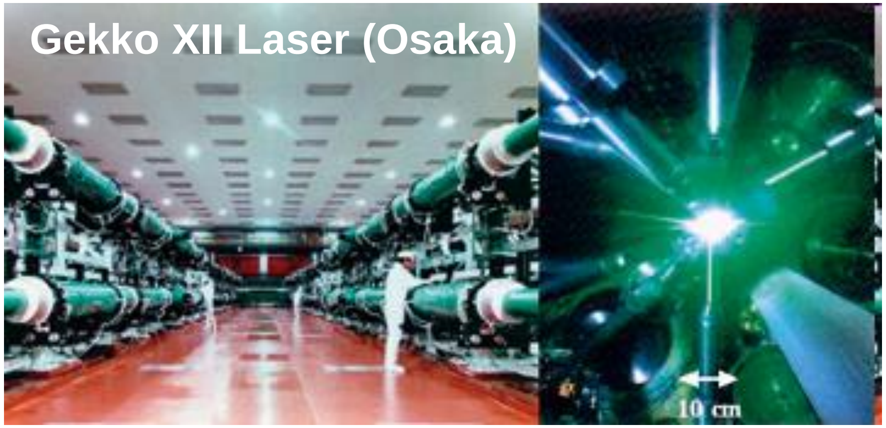
> 12,700 eV above Atom ground state

Electron impact excitation rate 4d $^1S_0$

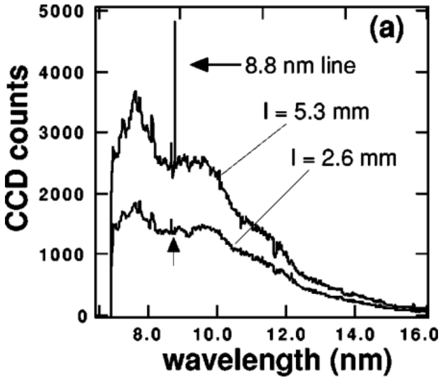


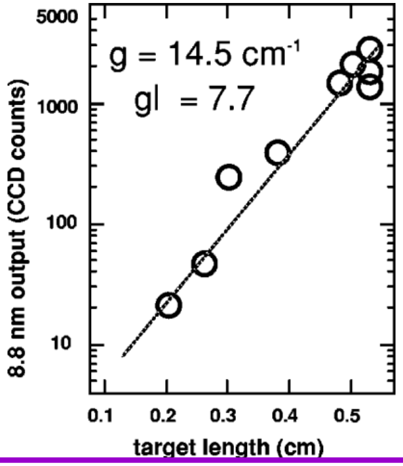
Previous work achieved unsaturated lasing at 8.8 nm in Ni-like La

*•Daido et al. using **520 J** of laser pump energy (Optics Lett. 21, 958,1996)*

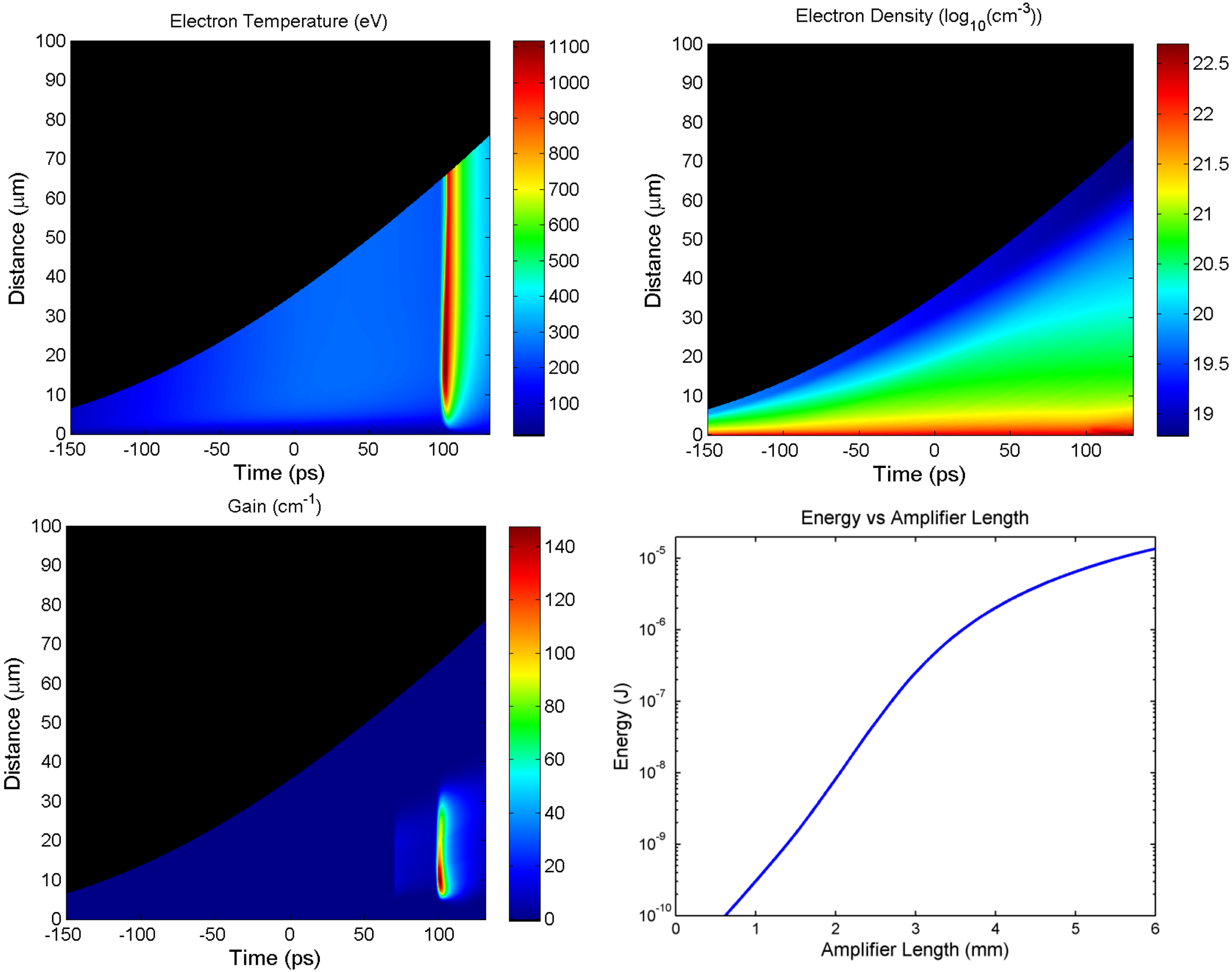


*Kawachi et al. using **18 J** picosecond pulses (Phys. Rev. A, 69, 2004)*





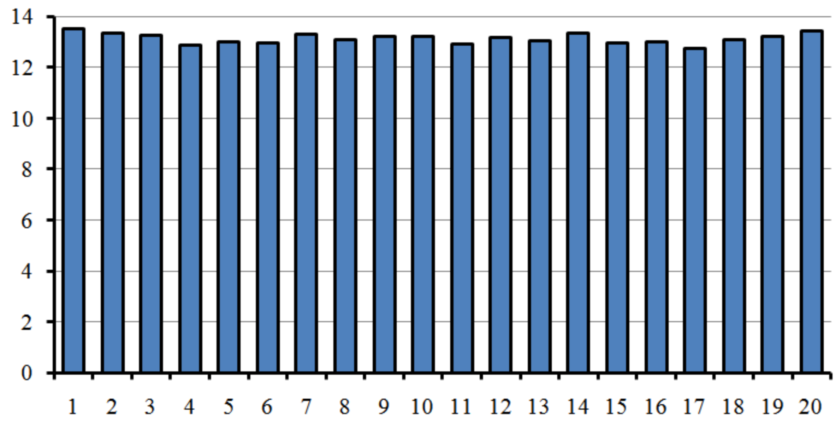
Simulation for 8.8 nm table-top Laser in Ni-like La predicts < 7 J pump energy needed for gain saturation

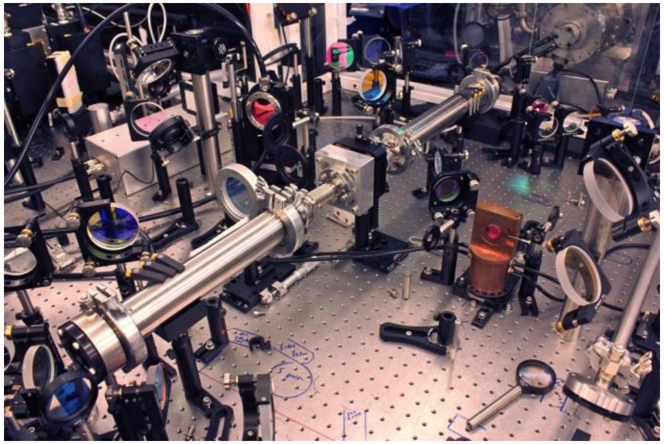


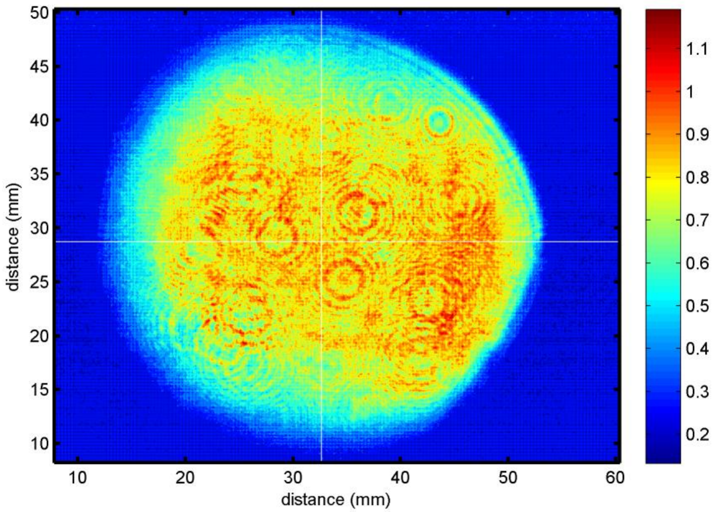
Simulation by Mark Berrill

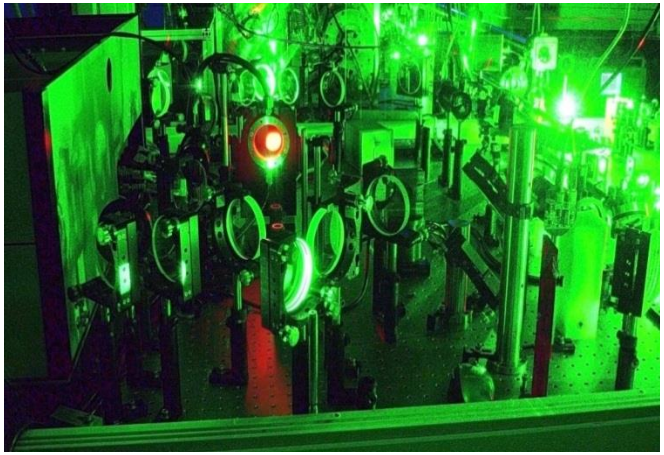
Titanium-Sapphire pump laser

Average Energy Pre-compression= 13 J
Std div. = 1.5 %

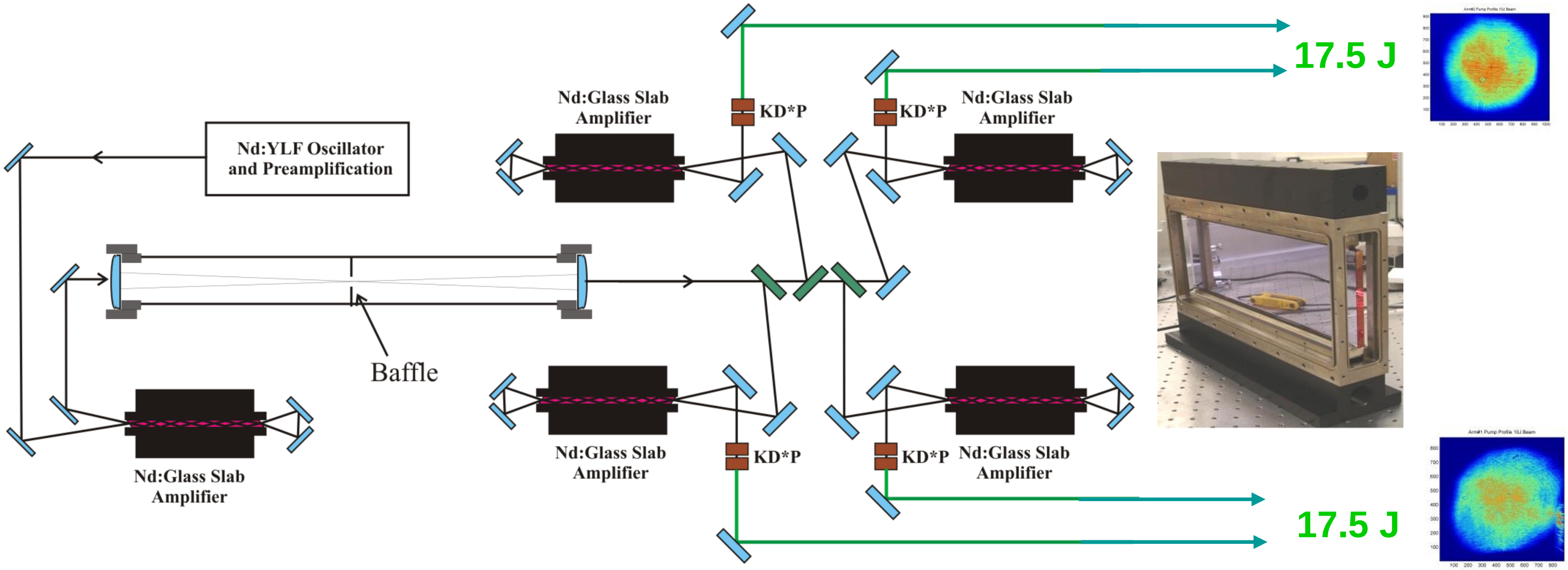




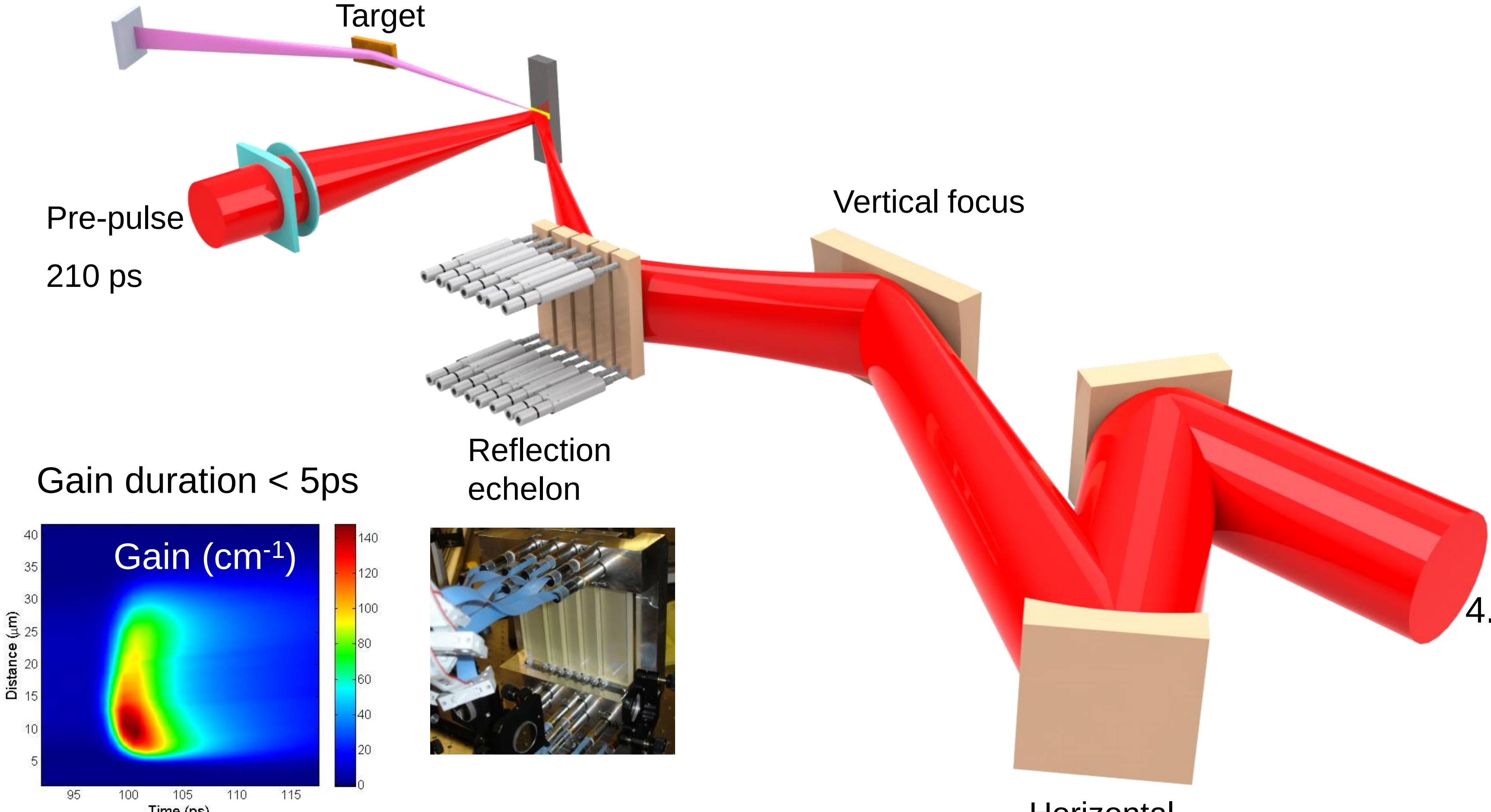




High energy pump laser for Ti:Sapphire: 35 J at 527 nm

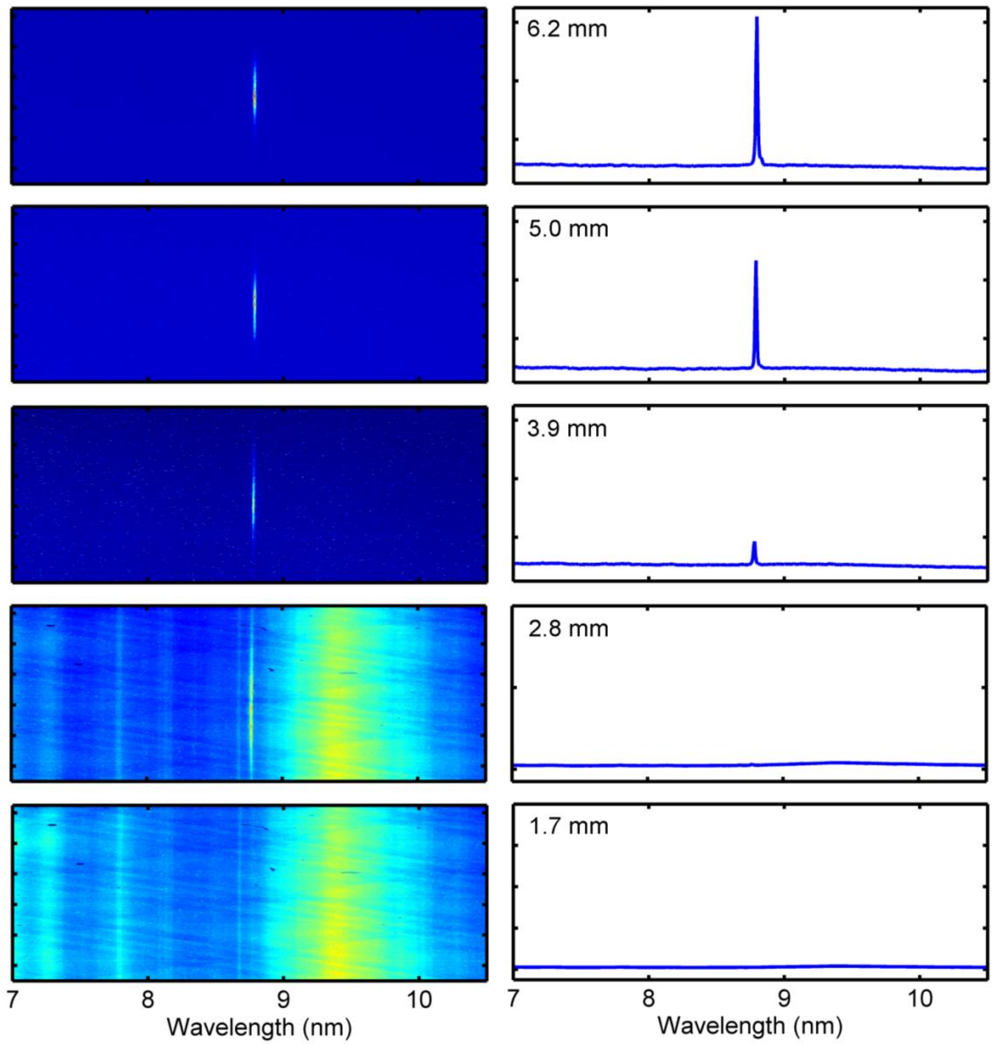


Gain-saturated sub-10 nm table-top lasers



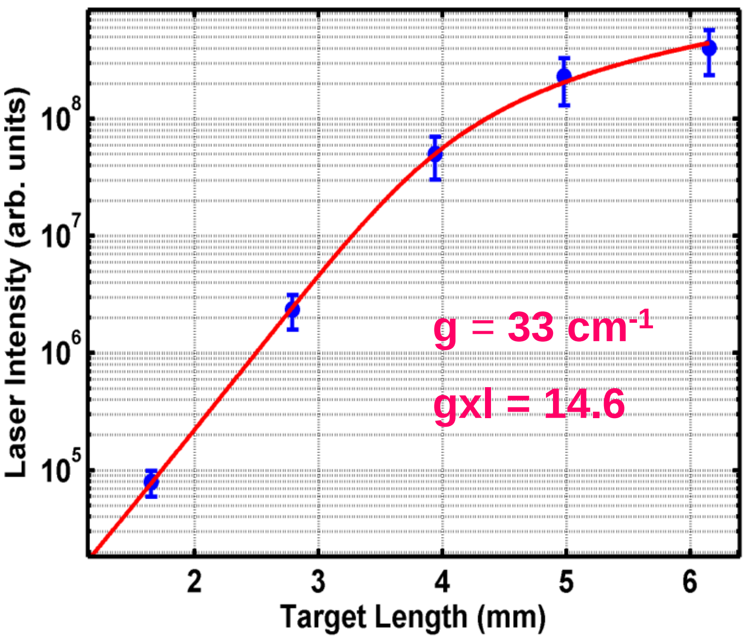
Demonstration of Gain-saturated table-top laser at 8.8 nm at 1 Hz repetition rate

Ni-like Lanthanum $4d^1S_0$- $4p^1P_1$



7.5 J Total Pump Energy

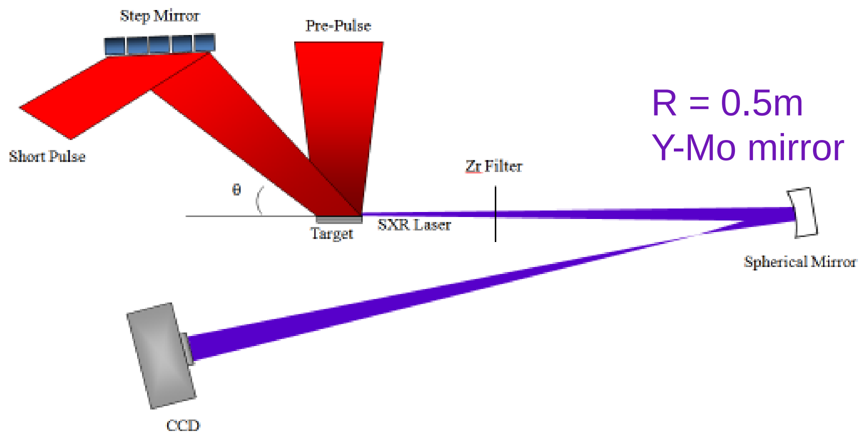
Pulse energy up to ~ 2.7 μJ

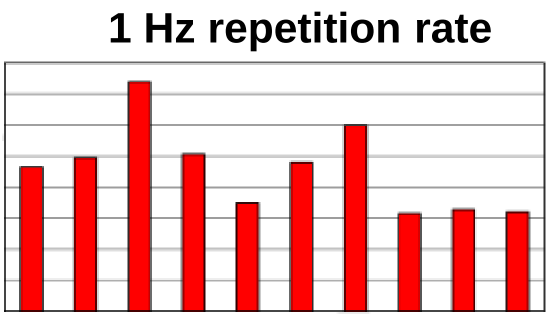


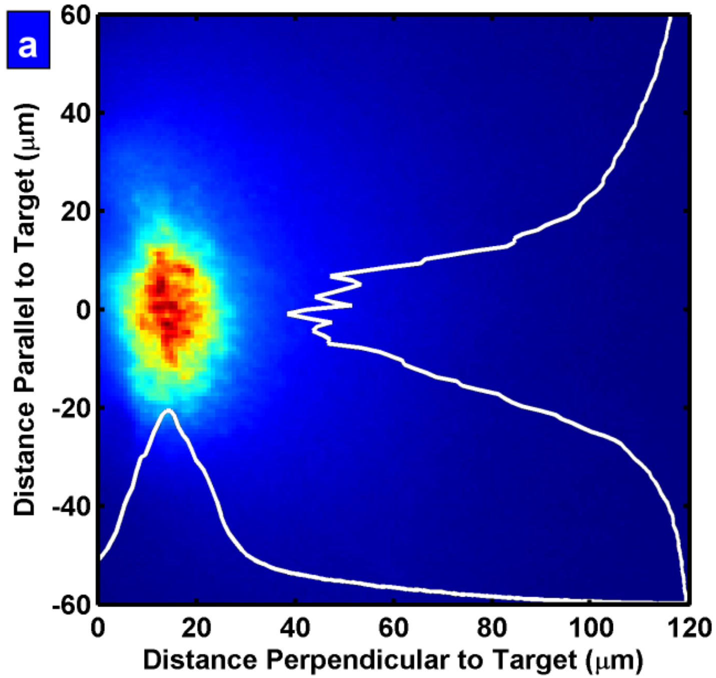
D. Alessi et al. Phys. Rev. X ,1, 021023 (2011)

1 Hz λ= 8.8 nm laser output intensity exceeds computed saturation intensity by an order of magnitude

Near field beam profile measurement







SXRL Fluence: 0.6 J cm^{-2}

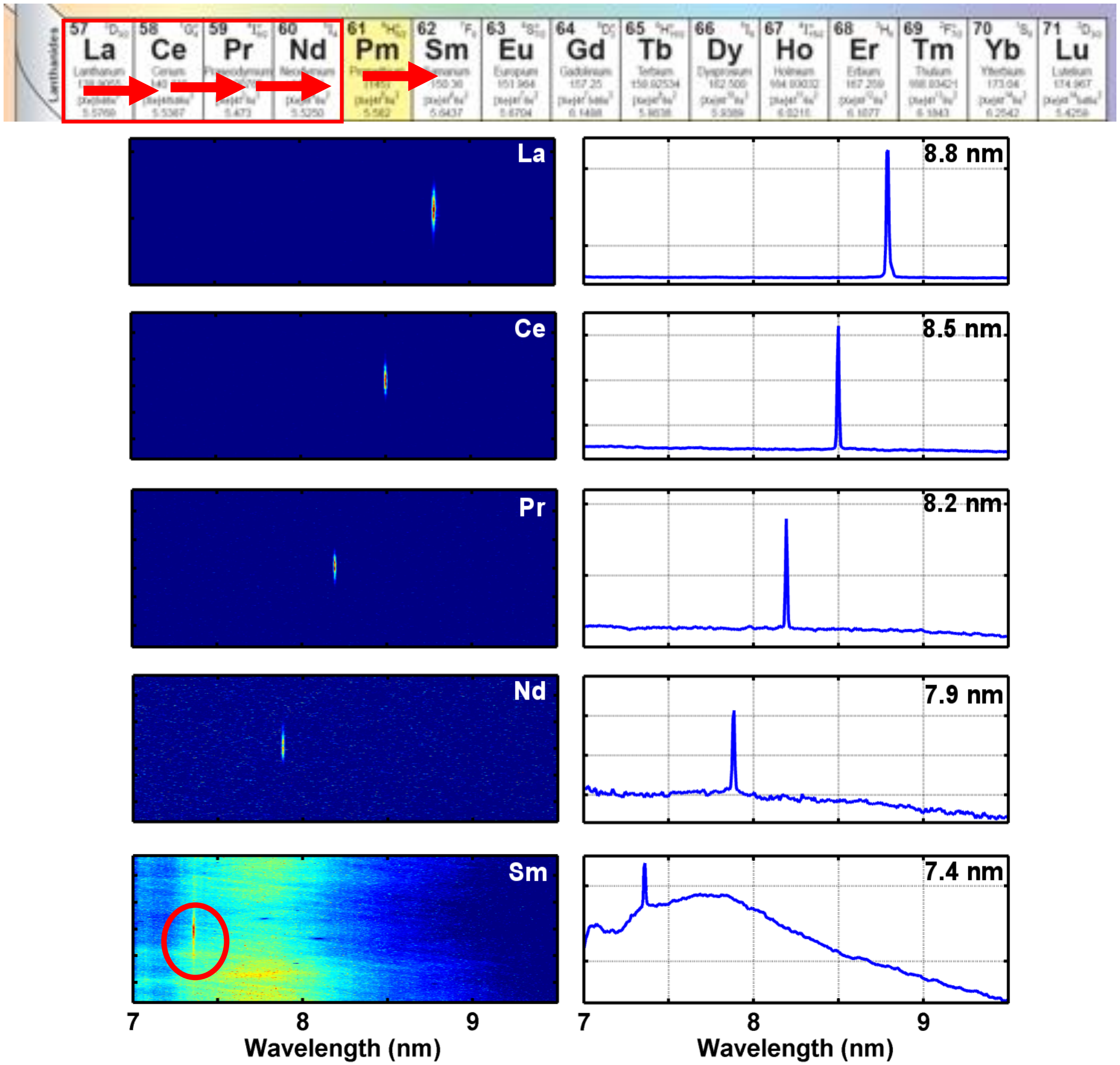
Experiment: I ~ 2.4 x 10^{11} W cm^{-2}

Computed I$_{sat}$: ~3 x 10^{10} W cm^{-2}

D. Alessi et al. Phys. Rev. X ,1, 021023 (2011)

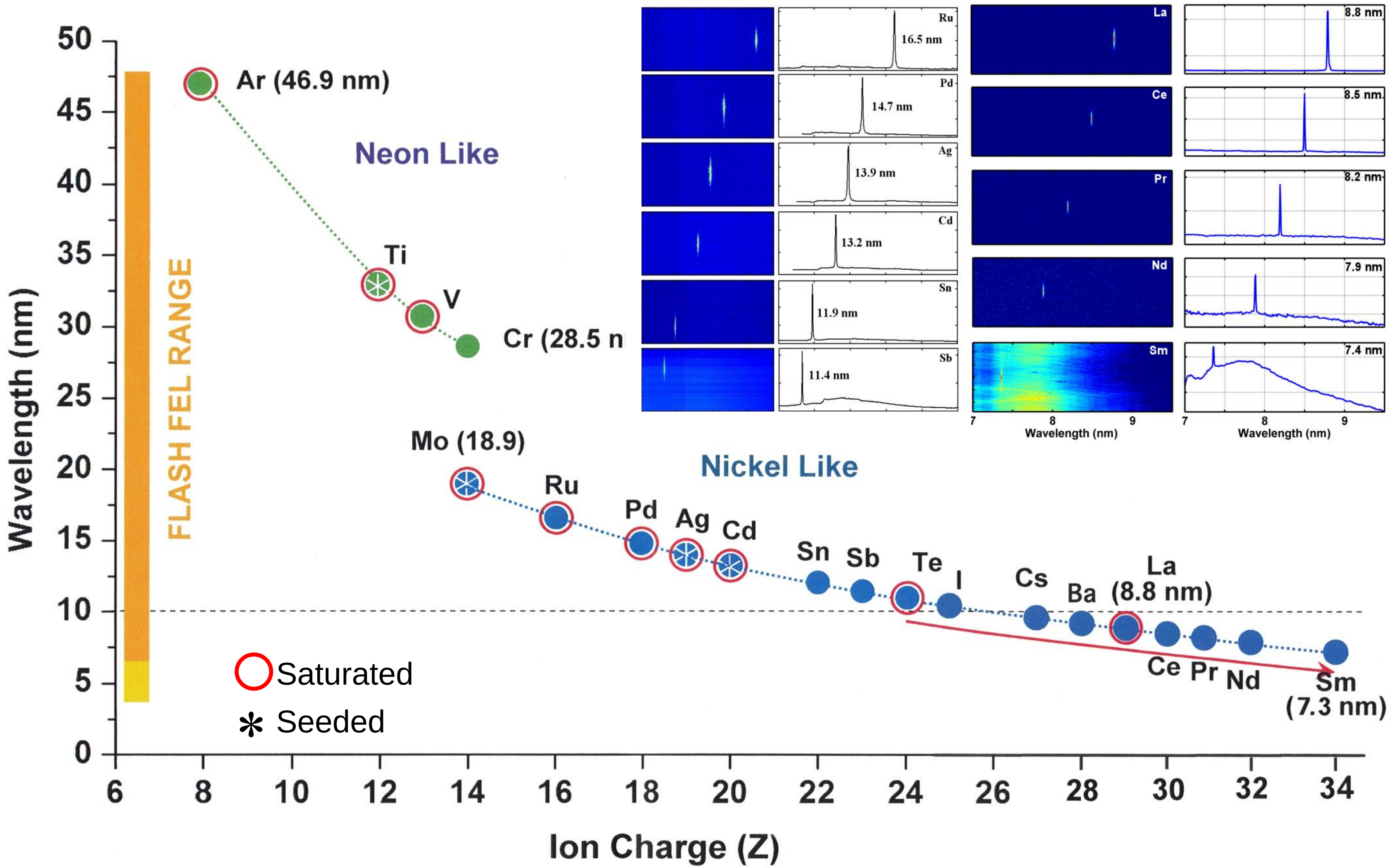
Lasing in transitions down to 7.36 nm

Nickel-like lanthanide ions $4d^1S_0$- $4p^1P_1$



D. Alessi et al. Phys. Rev. X ,1, 021023 (2011)

Gain-saturated table-top SXRLs cover 8.8 nm - 47 nm wavelength region



D. Alessi et al. Phys. Rev X, 1, 021023, (2011)

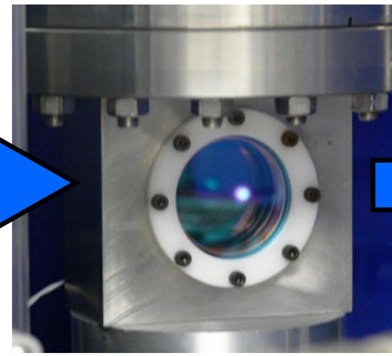
EUV
An NSF Engineering Research Center

The Next Generation: Increasing the repetition rate of Table-Top Soft X-Ray Lasers to 100 Hz

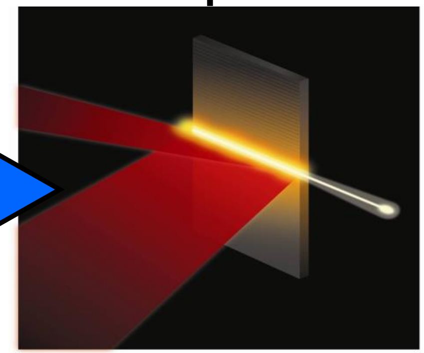
Colorado State University

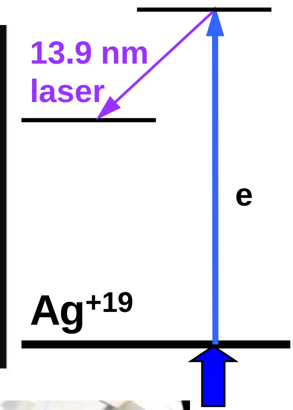
Laser Diode Drivers

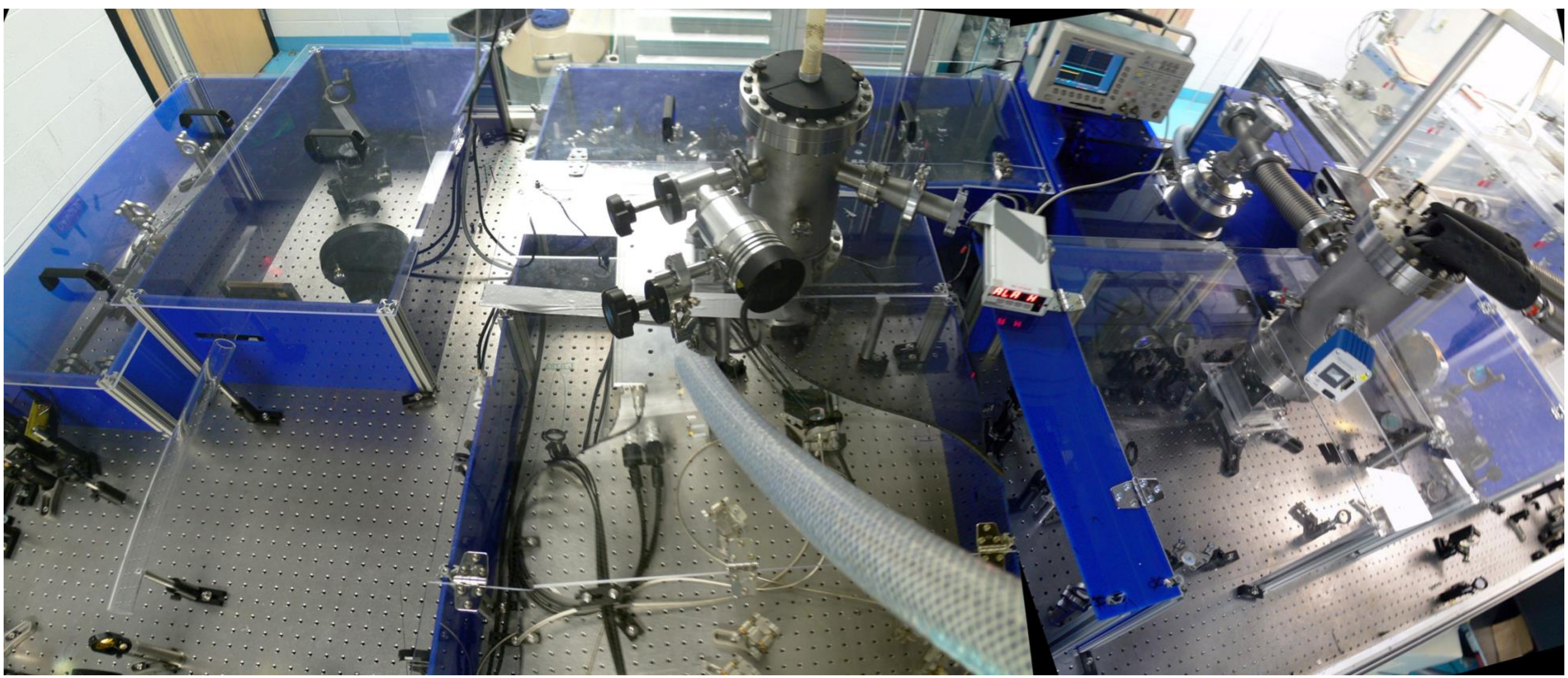
Solid State Ultrashort Pulse High Power Laser



Soft X-Ray Plasma Amplifier

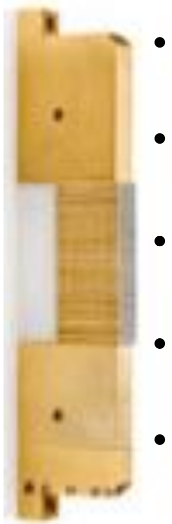






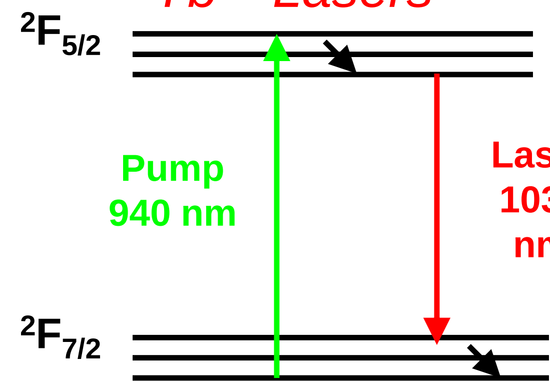
Directly diode-pumped Yb CPA laser increases repetition rate and average power

Laser Diode Pumping Advantages



- Highly efficient
  - >50% Electrical efficiency
- Narrow bandwidth
  - Efficiently pump a single transition
- Directional
  - End-pumping
- Very high average power
  - Allow high repetition rate
- Compact

Yb^{+3} Lasers

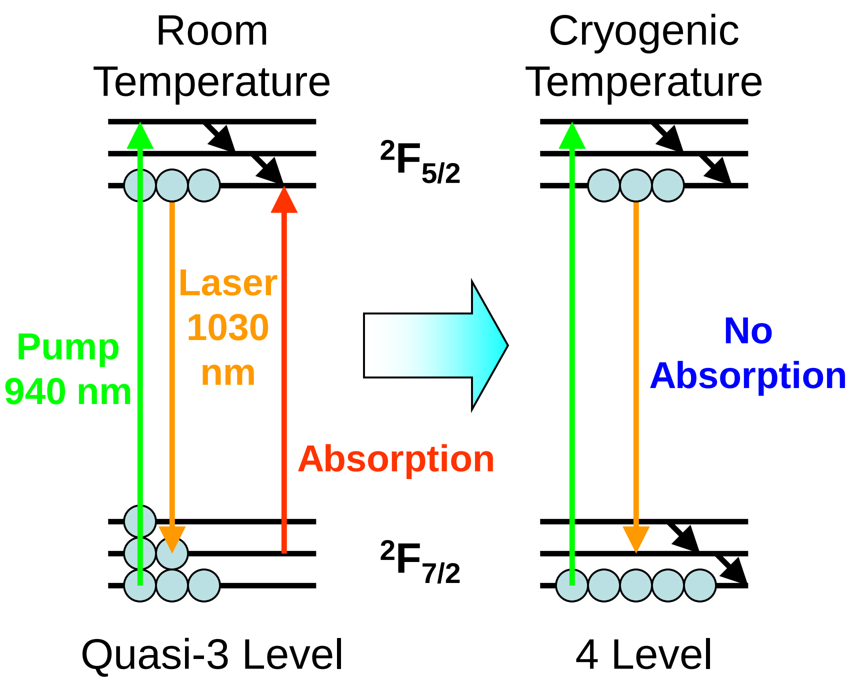


- Absorption bands at InGaAs wavelengths
- Very low quantum defect (<10%)
- Long lifetime for high energy storage

Thermal and gain properties of Yb:YAG are dramatically improved at cryogenic temperature

Yb:YAG at room and cryogenic temperature	300 K	77 K	
Thermal conductivity (W/mK)	10	90	x9
Thermo-optic coefficient (10^{-6}/K)	7.8	0.9	x1/7
Expansion coefficient (10^{-6}/K)	6.14	1.95	x1/4
Saturation fluence (J/cm^2)	9.2	1.7	x1/7

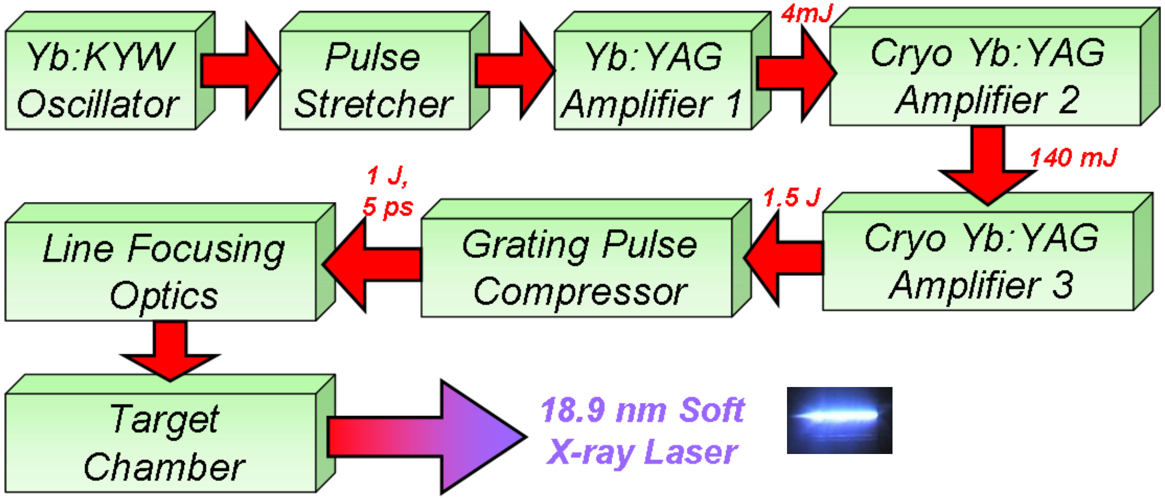
G. A Slack and D. W. Oliver; Phys. Rev. B4; 592-609 (1971)
R. Wynne, J. L. Daneu and T. Y. Fan; Appl. Opt. 38, 3282-3284 (1999)
R.L. Aggarwal, et. al., Journal of Applied Physics, 98, 103514, (2005).



Other recent cryogenic diode-pumped CPA work:

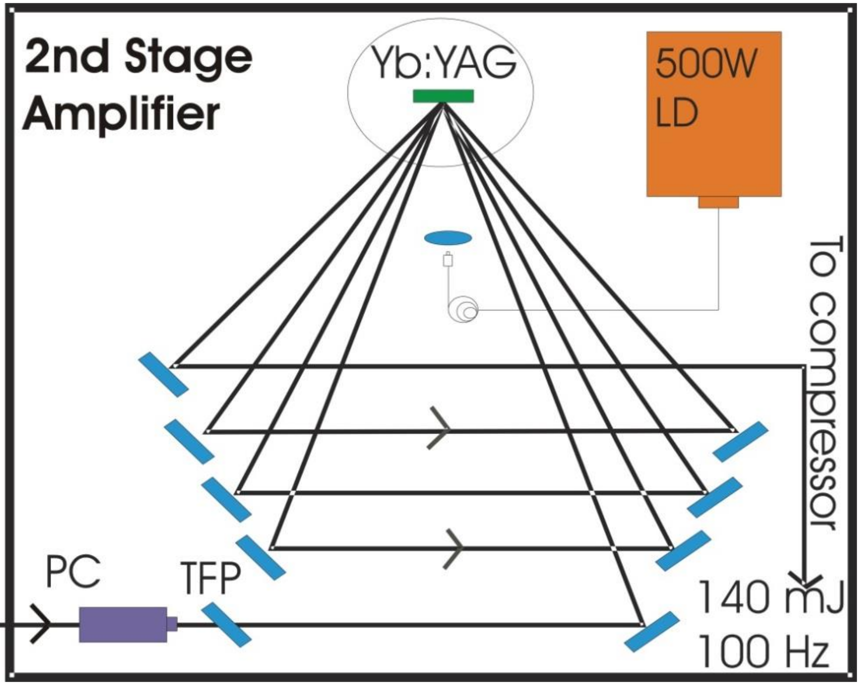
1. *K.H. Hong, et al., Optics Letters* ***35****, 1752, (2010).*
2. *D. Rand, et al., CM3D.4 CLEO 2012.*
3. *D.E. Miller, et al., CM3D.2 CLEO 2012.*
4. *K. Ogawa, et al., CMB.4, CLEO 2011.*

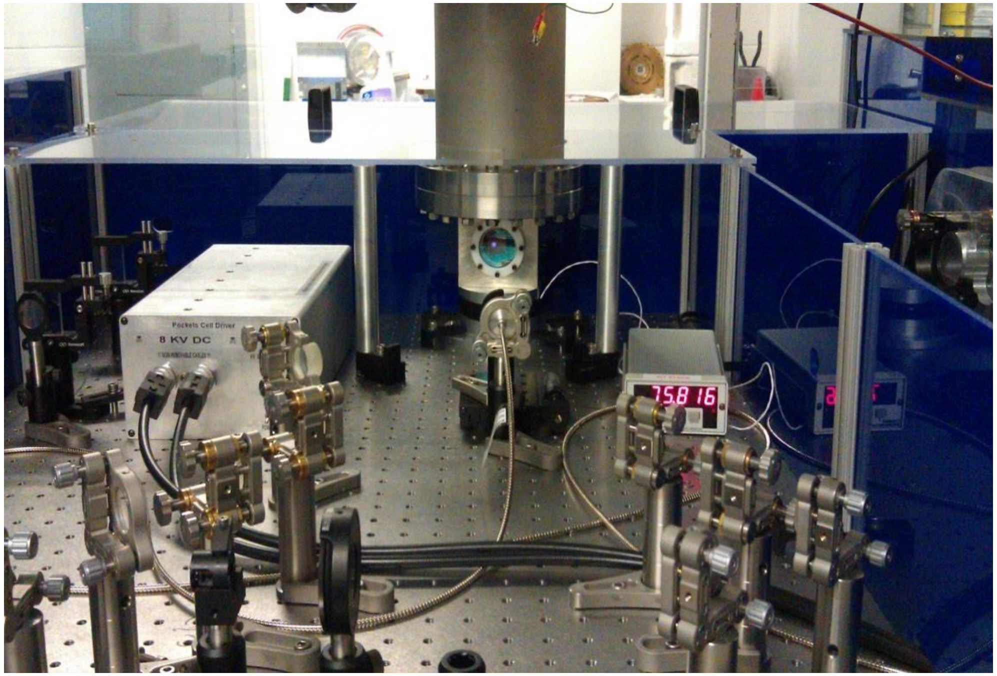
Compact high power diode-pumped CPA laser driver for 100 Hz table-top SXRL



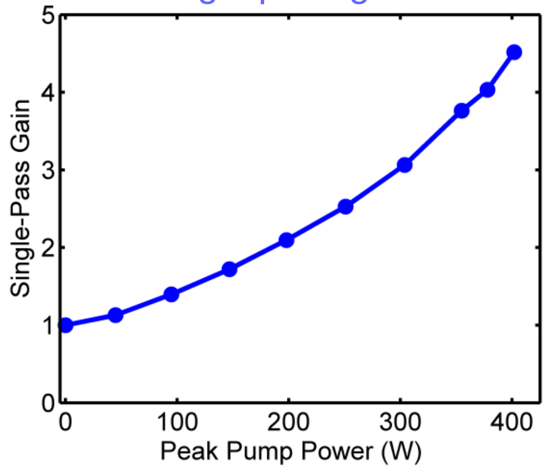
2nd stage cryo-cooled Yb:YAG amplifier

140 mJ, 100 Hz, amplifier operation demonstrated

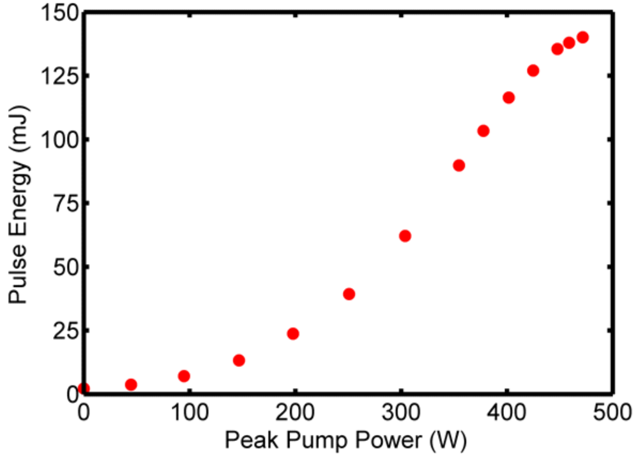




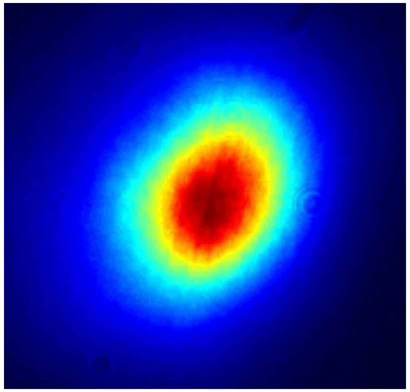
Single pass gain



Pulse energy

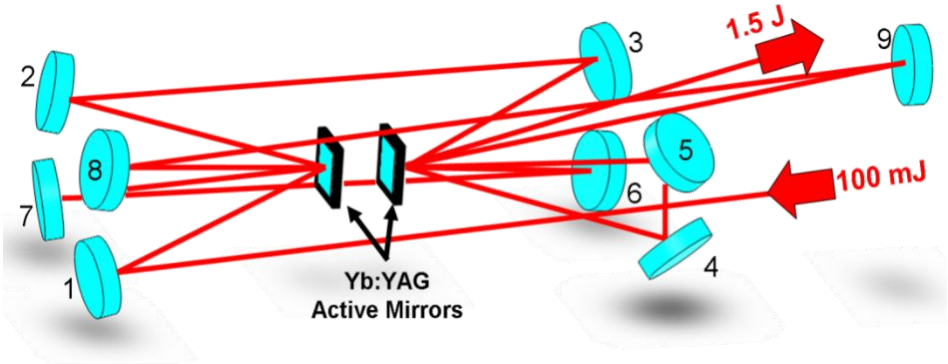


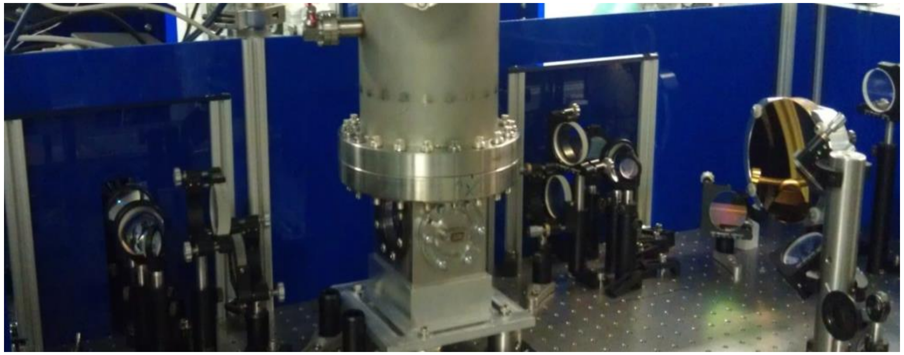
Beam pattern



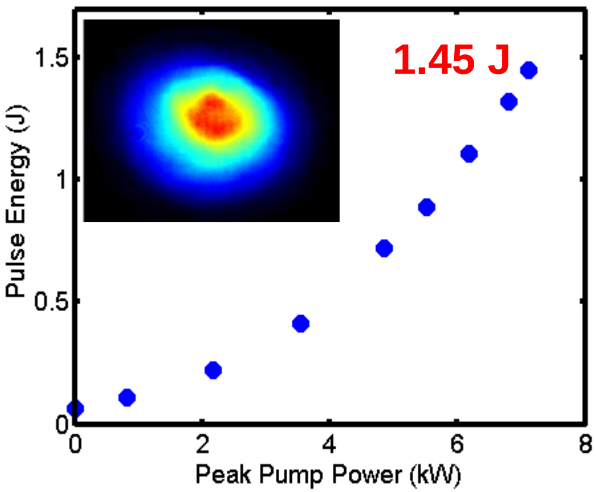
A. Curtis et al. Optics Letters, 36, 2164, (2011)

100 Hz repetition rate 1.5 Joule diode-pumped cryo-cooled Yb:YAG amplifier

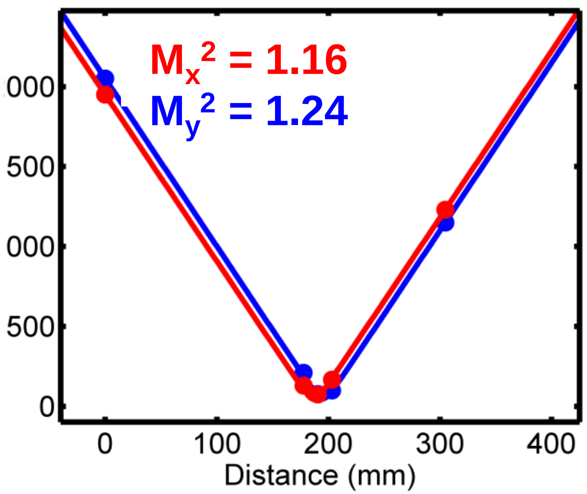




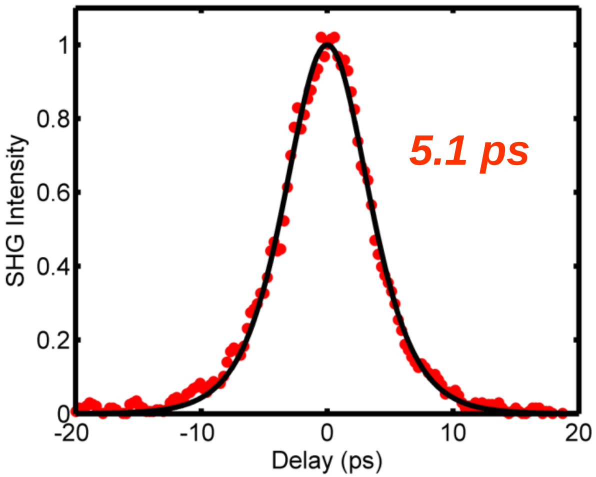
Uncompressed pulses



M^2 of amplified pulses

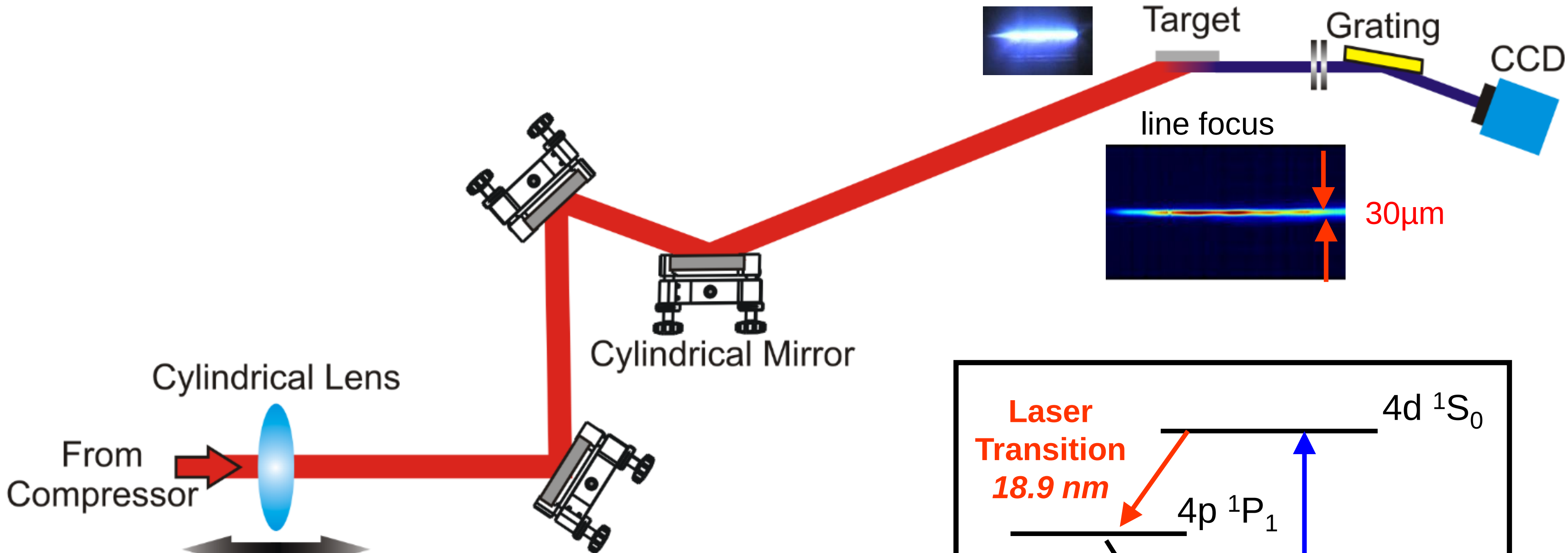


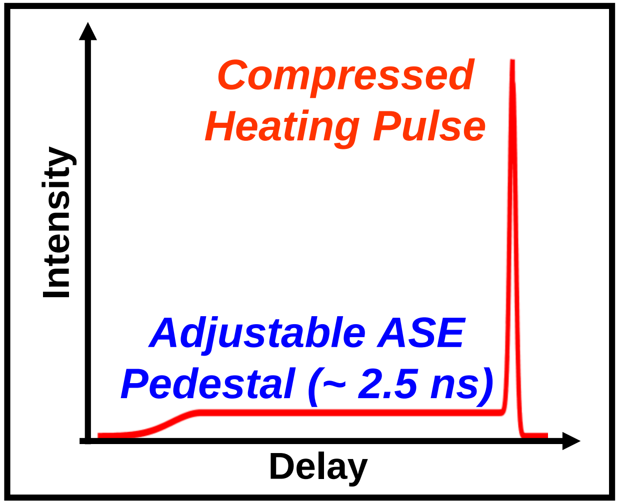
2^{nd} order autocorrelation of compressed 1 J pulses

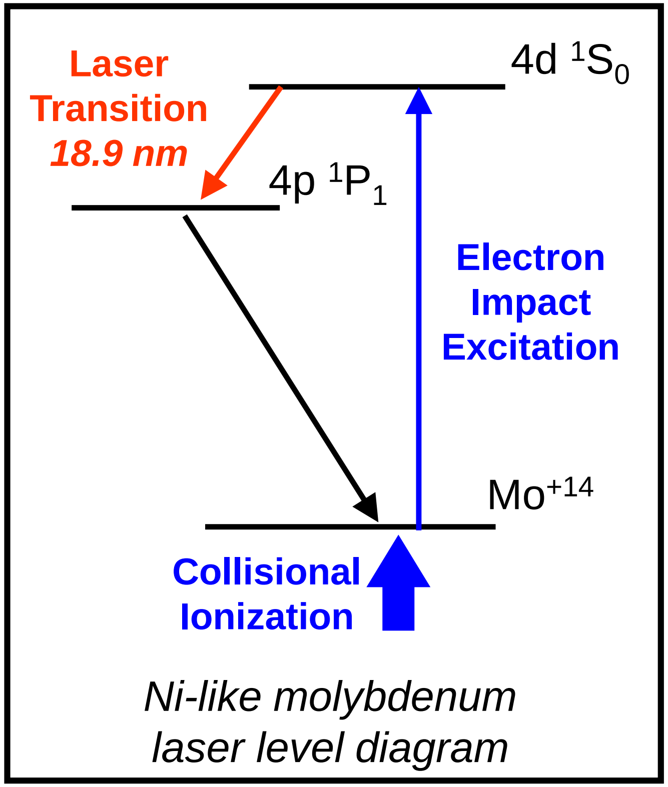


***1 J, 5 ps* pulses at 100 *Hz* repetition rate**

Soft X-Ray laser employs ns ASE pedestal followed by ps pump pulse from same CPA diode-pumped laser

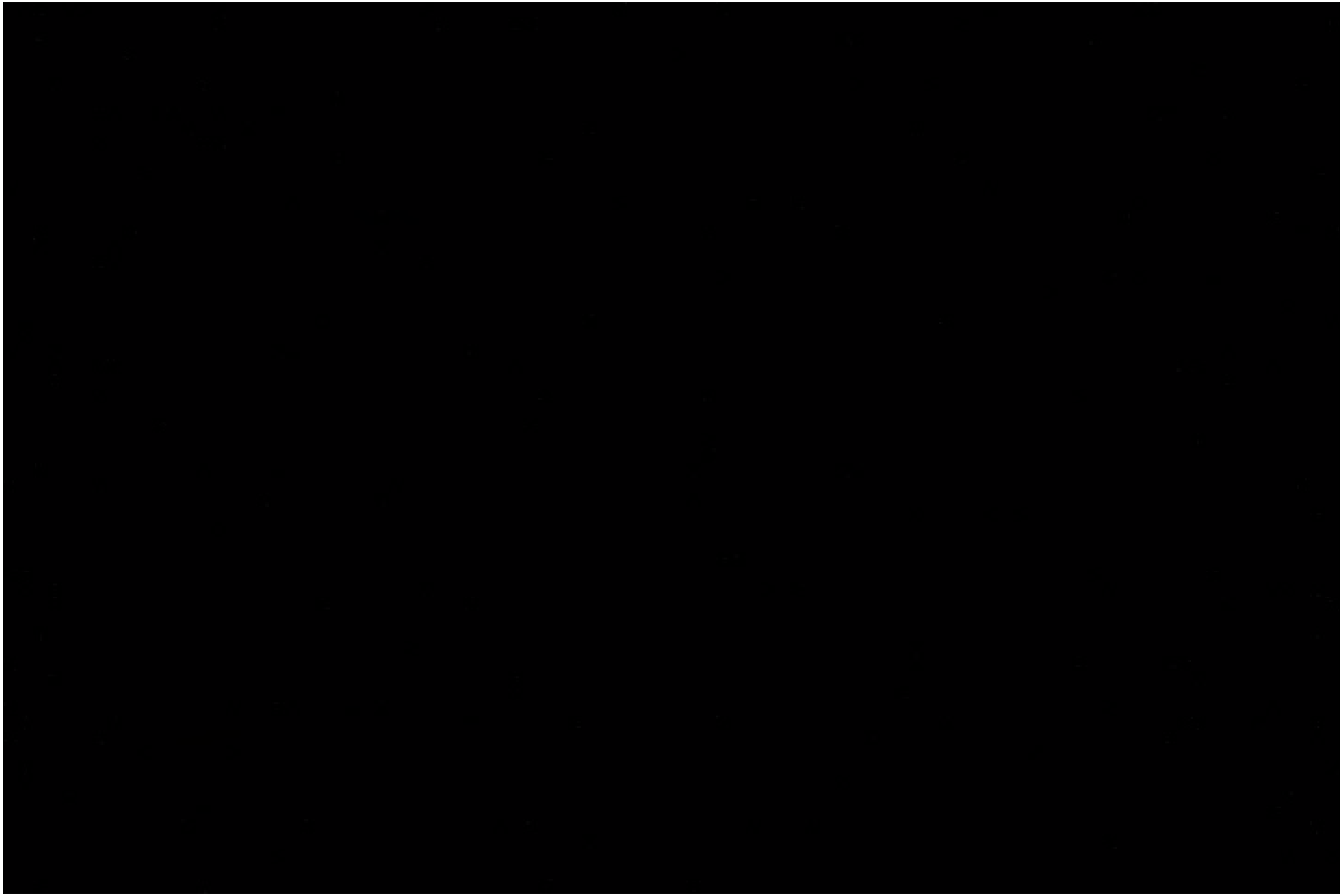






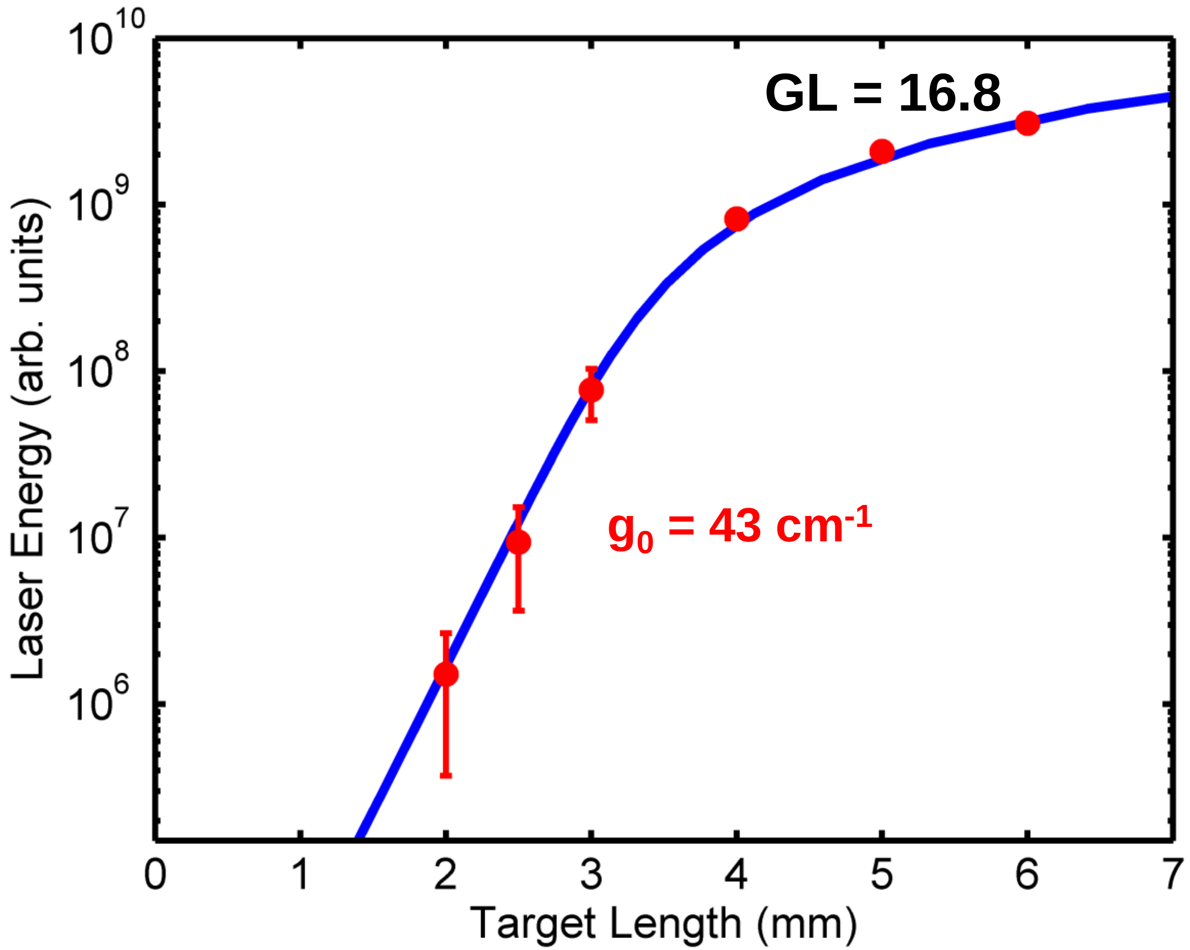
B. Reagan et al., Optics Letters (2012)

100 Hz Operation



Gain-Saturated 18.9nm Laser Operation at 100 Hz repetition rate

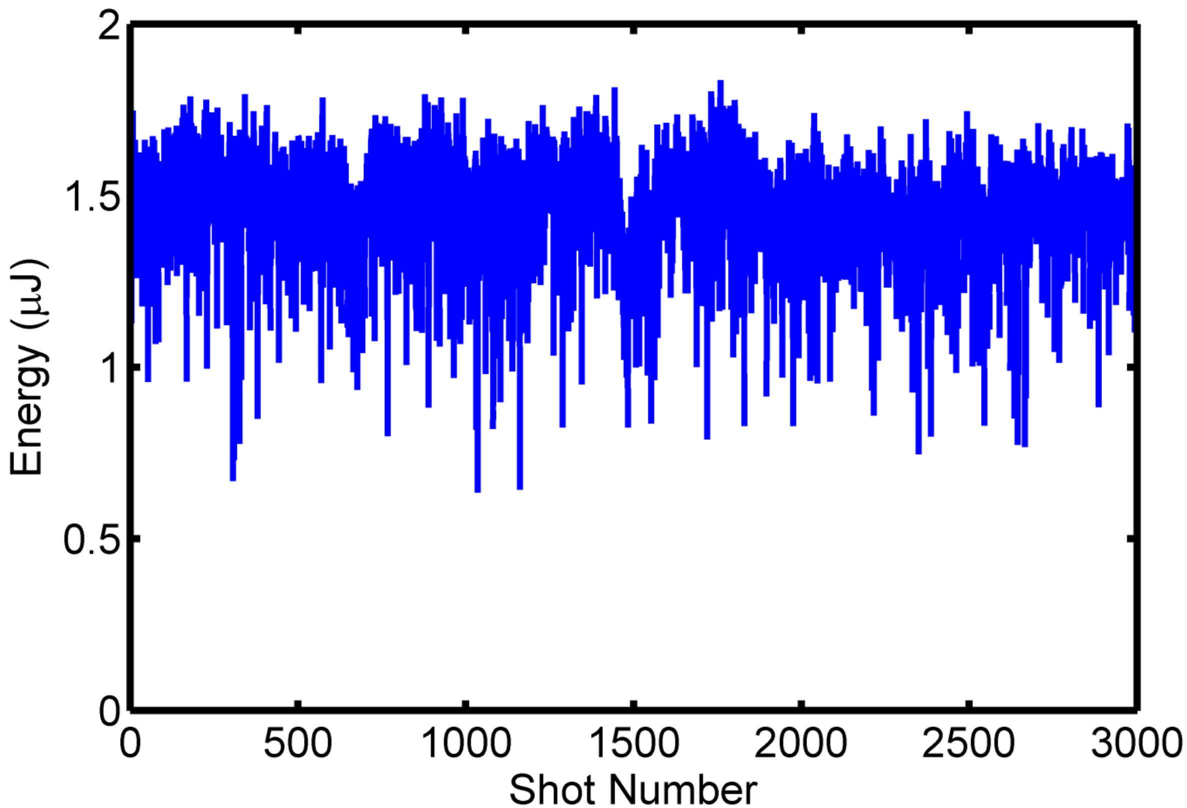
Pump: 970 mJ on target



B. Reagan et al., Optics Letters (2012)

100 Hz, 18.9 nm laser

940 mJ on target target moved at 200 um/s, (2um/shot)

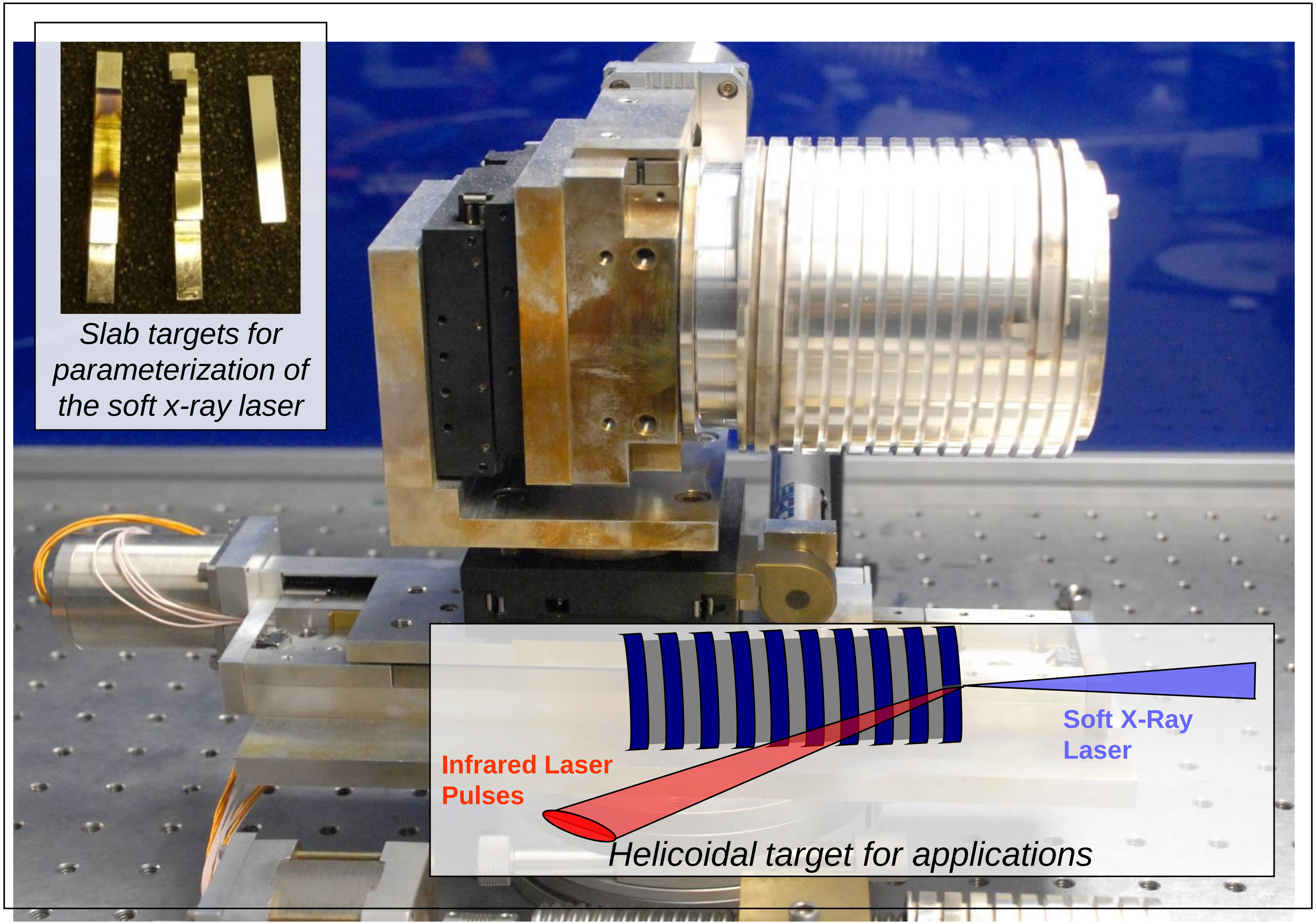


Mean Energy = 1.46 μJ, σ = 11%

0.15 mW average power

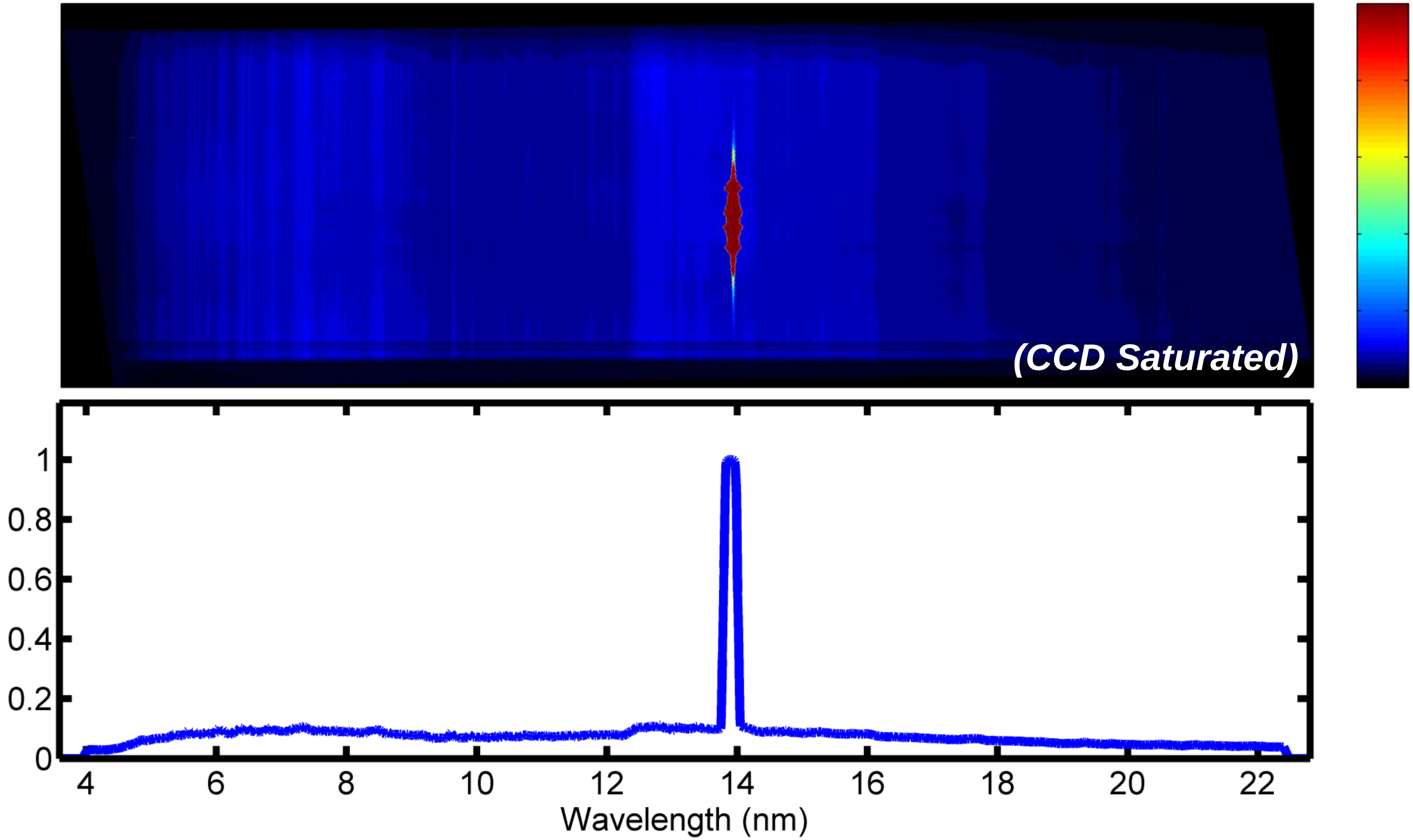
(Fermi FEL 20-65 nm: 30-60 uJ x 10 Hz = 0.3-0.6 mW Luca Giannessi ICXRL)

Helicoidal targets developed to allow continuous operation at 100 Hz repetition rate



A. Weith et al. Optics Letters, 31, 1994, (2006)

Demonstration of *all-diode-pumped laser* at 13.9nm in Ni-like silver plasma

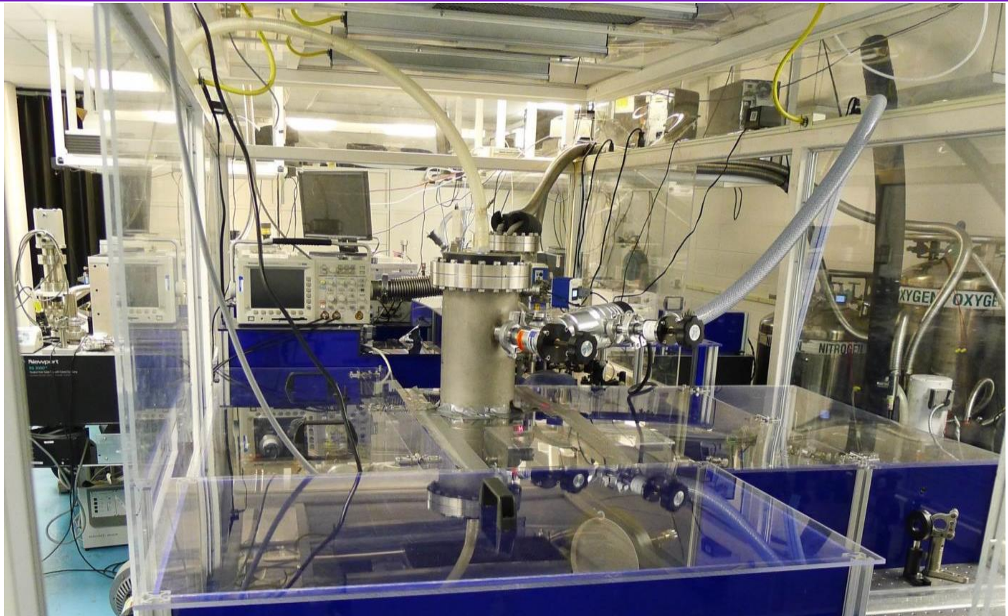


Single-shot spectrum of Ag plasma, 950 mJ pulse energy on target
Driver laser operating at 50 Hz repetition rate.

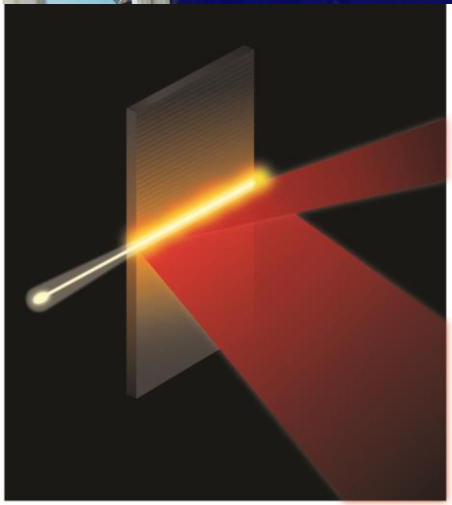
B. Reagan et al., Optics Letters (2012)

Summary

• Gain-saturated table-top SXRLs reach λ= 8.85 nm. Amplification observed down to λ= 7.3



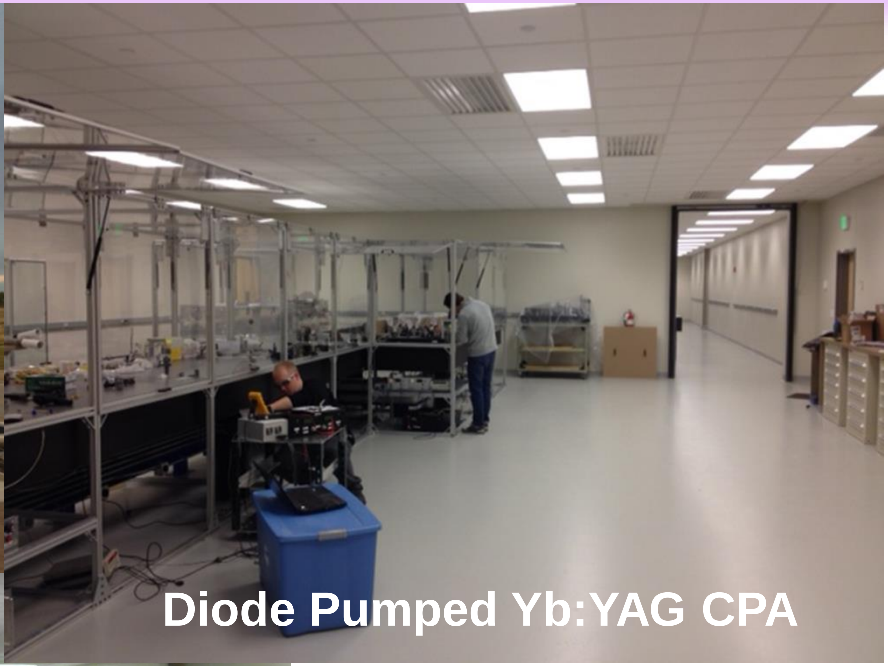
• Compact diode-pumped soft x-ray laser operating at record 100 Hz rep. rate produces 0.15 mW average power on a table-top



Work Supported by the NSF Engineering Research Centers Program and the US Department of Energy

Acknowledgement

New Facilities are allowing to expand optical drivers for secondary radiation generation



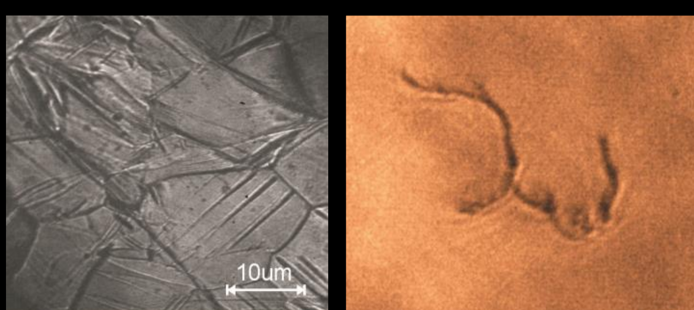
Photonics at extreme ultraviolet and soft x-ray wavelengths on a table-top

Carmen S. Menoni
Center for Extreme Ultraviolet Science and Technology
Department of Electrical & Computer Engineering
Department of Chemistry
Colorado State University

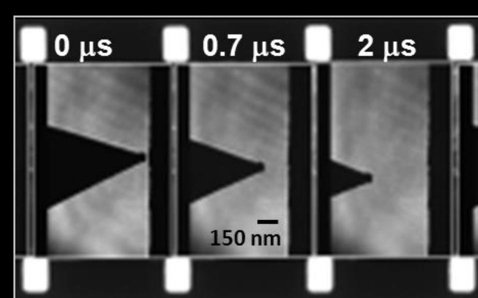
IEEE Distinguished Lecture

IEEE photonics SOCIETY

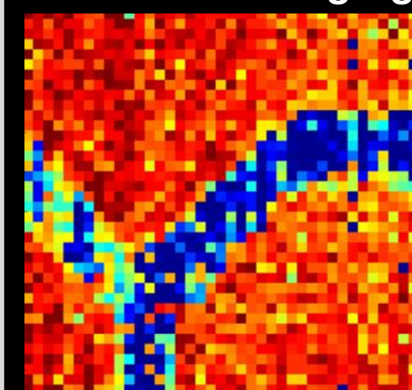
Imaging of nanostructures



Movies at the nanoscale

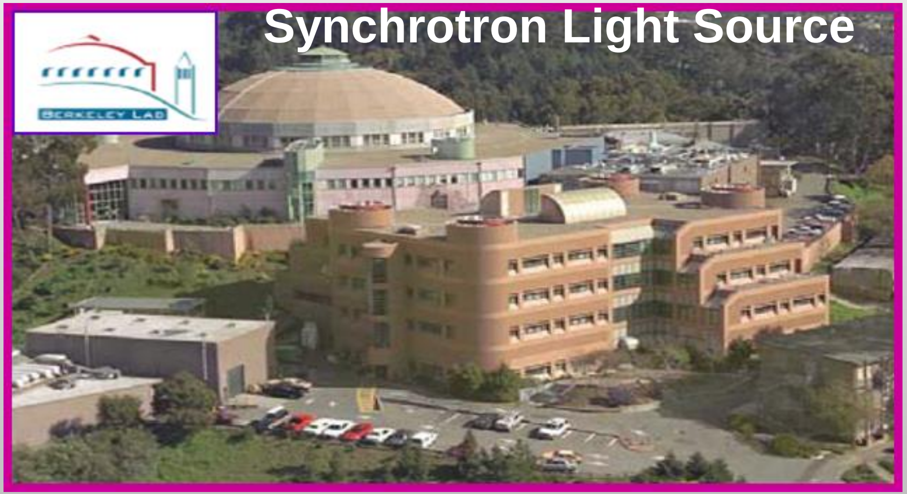


Molecular Imaging



EUV/SXR sources are paving the way to scientific research and technological innovation

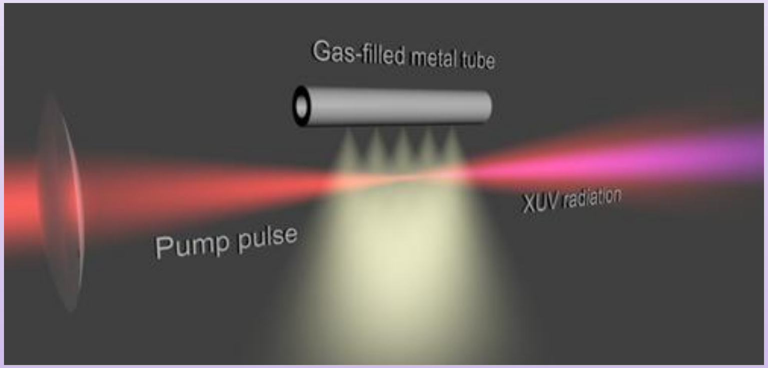
PHOTON FACTORIES



COMPACT SOURCES

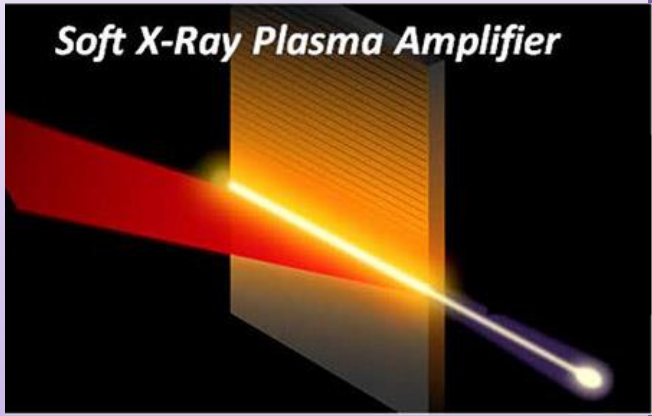
Incoherent sources

High Harmonic Generation

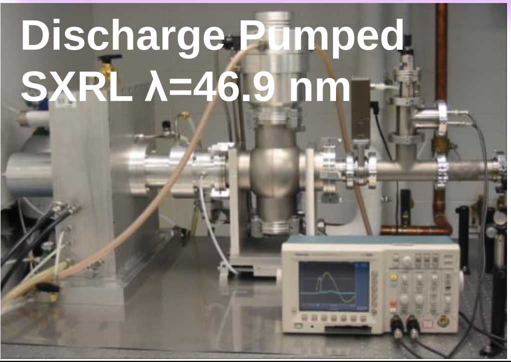


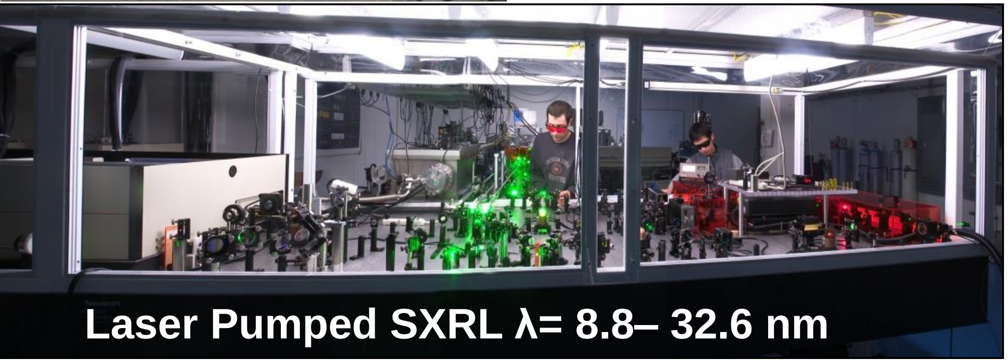
http://www.ino.it

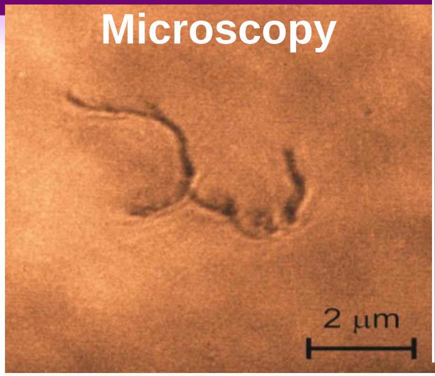
Lasers

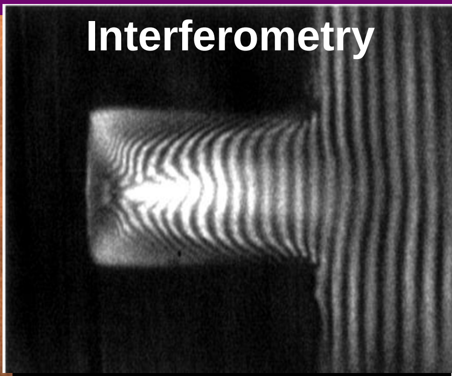


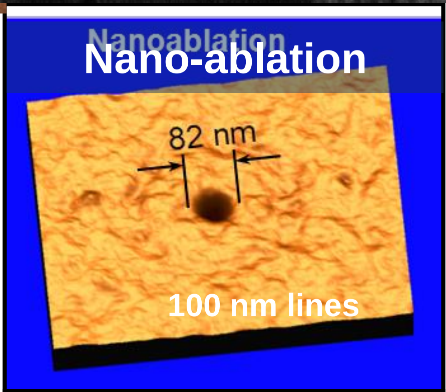
Compact plasma-based soft x-ray lasers can be installed at the application's site



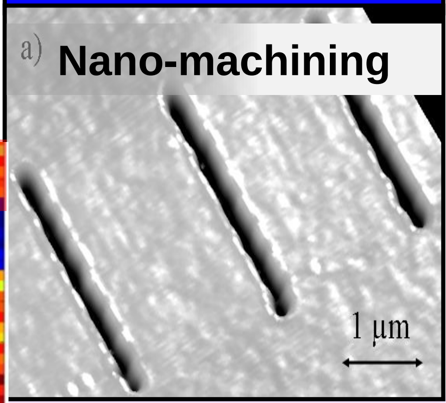


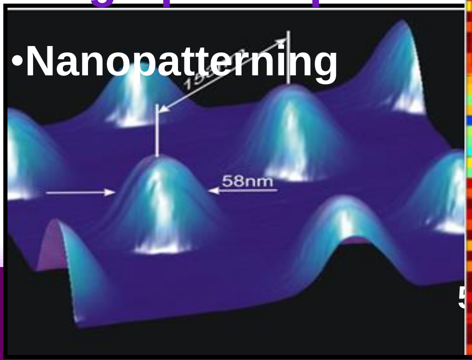


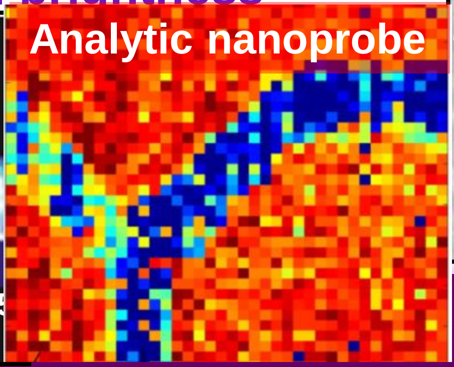




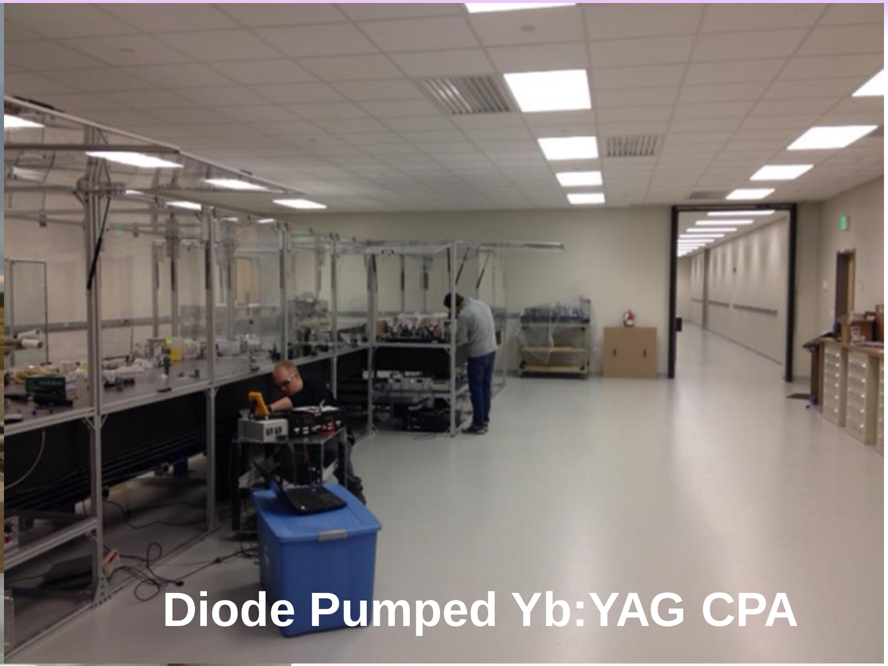
- High pulse energy (µJ-mJ)
- High monochromaticity ($\lambda/\Delta\lambda < 10^{-4}$)
- High peak spectral brightness



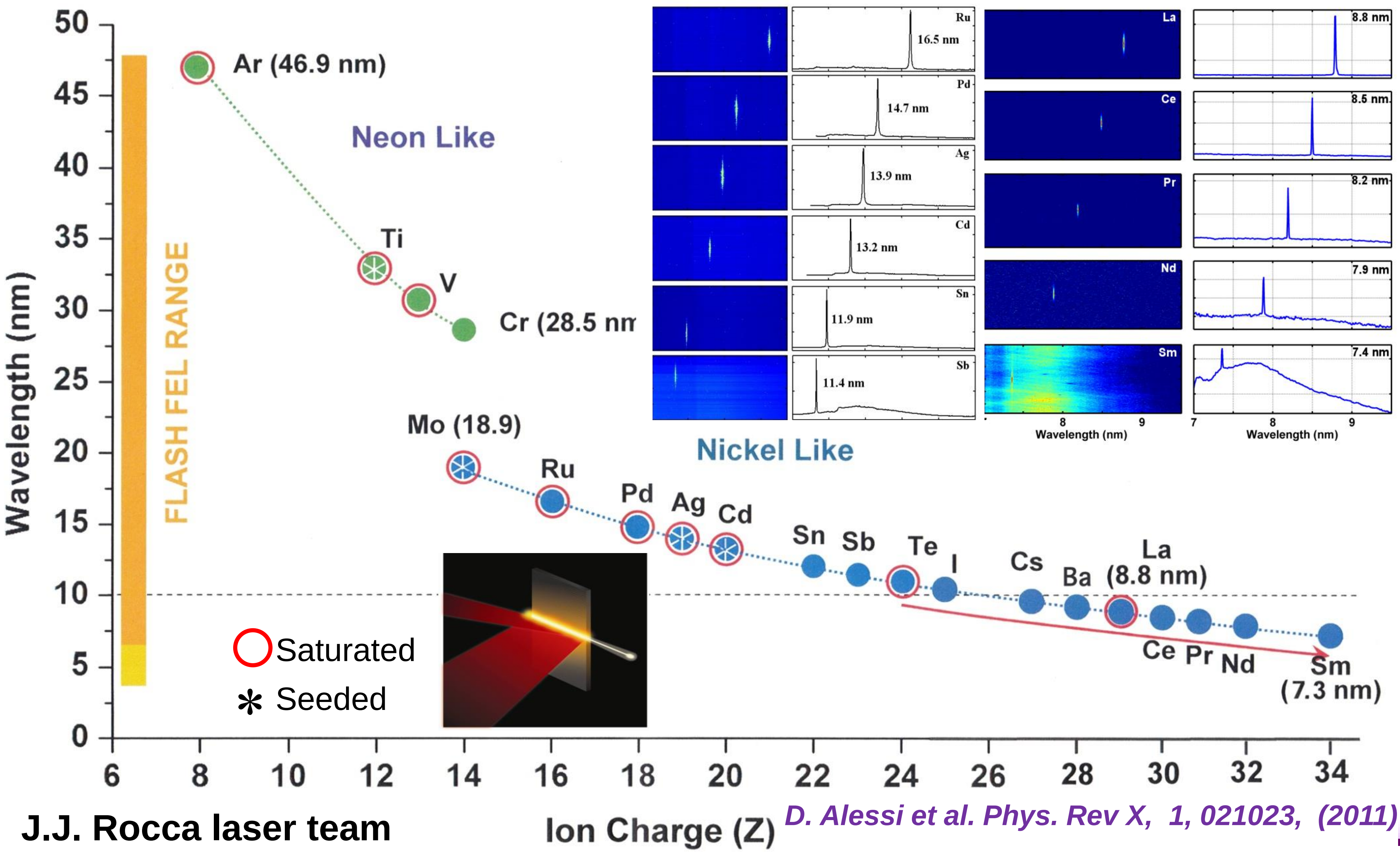




New Facilities are allowing to expand optical drivers for secondary radiation generation



Gain-saturated table-top SXRLs cover 8.8 nm - 47 nm wavelength region - Pump: CPA Ti:Sapphire

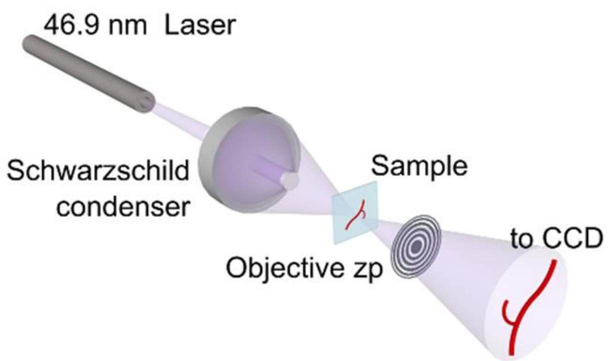


J.J. Rocca laser team

D. Alessi et al. Phys. Rev X, 1, 021023, (2011)

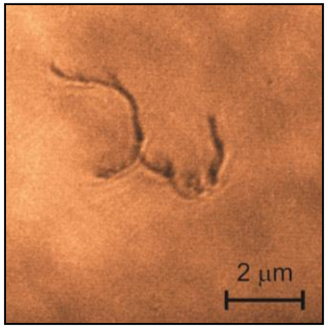
SXRL microscopes are critical photonic technologies for imaging nanostructures and surfaces

Transmission
λ=46.9 nm, 13.9 nm



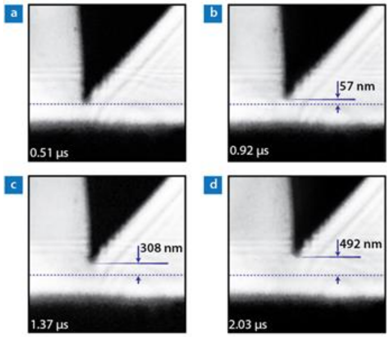
38 nm spatial resolution @ 13.9 nm
G. Vaschenko et al, Opt.Lett 2006

Single shot Imaging of nanostructures



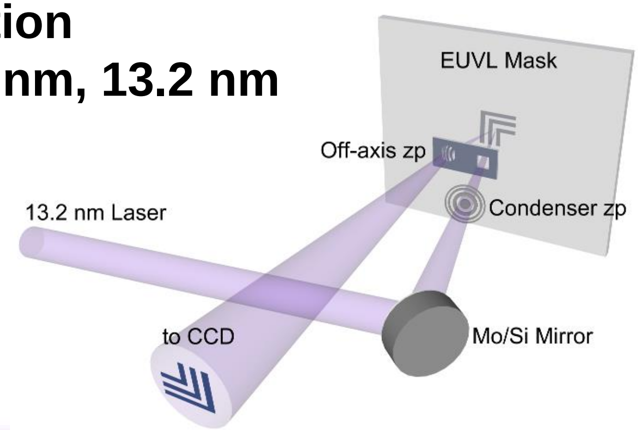
50 nm Carbon Nanotubes
Spatial resolution: 50 nm
C. Brewer et al, Opt.Lett 2008

Time resolved Imaging

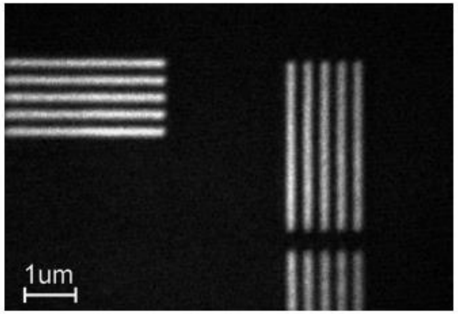


Frames from a SXR motion picture
S. Carbajo et al, Opt. Lett . 2012

Reflection
λ=46.9 nm, 13.2 nm



Aerial inspection of EUVL masks (λ=13.2 nm)

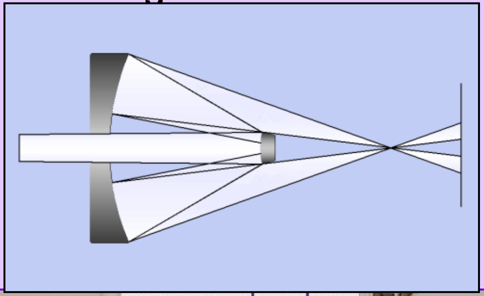


F. Brizuela et al, Op.Lett. 2009, Opt. Exp. 2010

Compact λ= 46.9 nm full field microscope

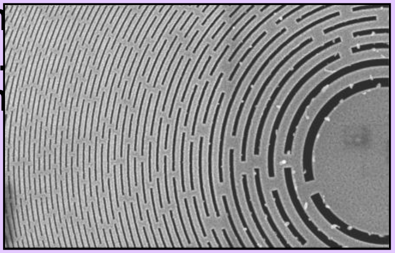
Laser Output Characteristics:
- Output Energy: > 10 µJ/pulse
- Repetition rate: up to 12 Hz
- Pulse duration: ~1.5 ns
- Bandwidth: $\Delta\lambda/\lambda < 1 \times 10^{-4}$
- Tailored spatial coherence

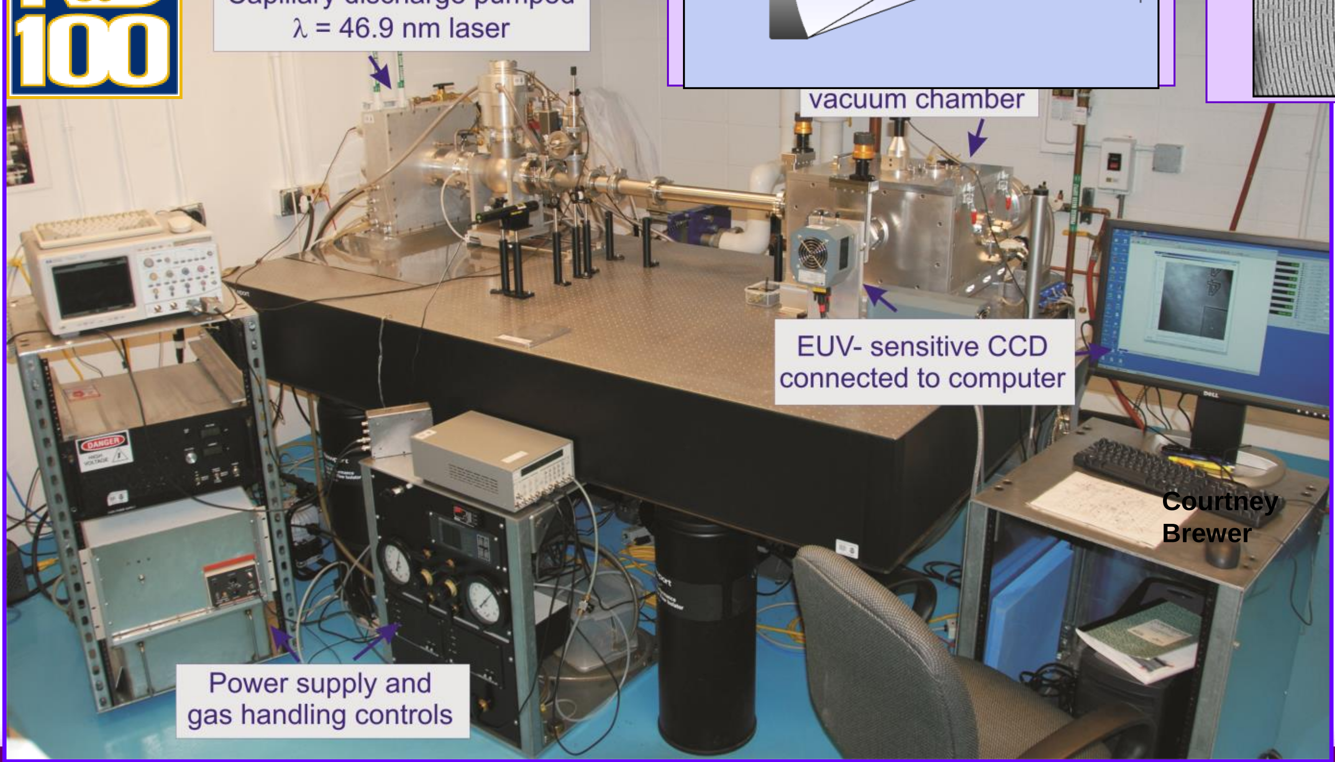
Sc/Si multilayer coated Schwarzschild condenser
Throughput: 13%
NA=0.18 ,
working distance: 60 mm



Freestanding Fresnel zone plate objective

NA	Δr	f
0.32	70 nm	0.75 mm
0.19	120 nm	1.28 m
0.		m

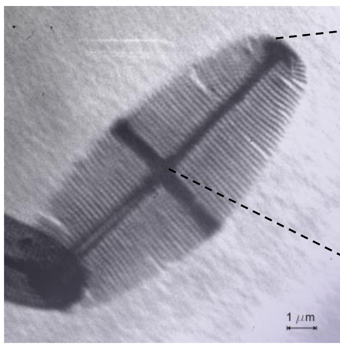


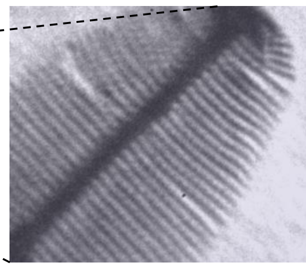


EUV/SXR microscope captures images of nanostructures with very high resolution

TRANSMISSION
NA=0.32 (M~1000)

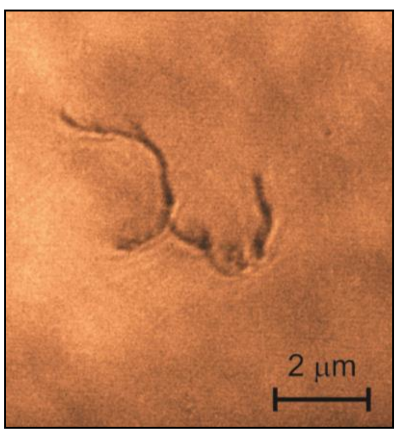
200 nm half period diatom





5 sec exposure

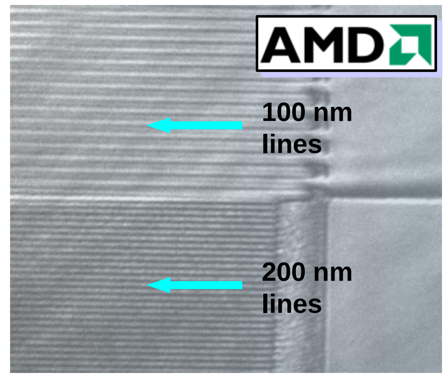
50 nm carbon nanotube



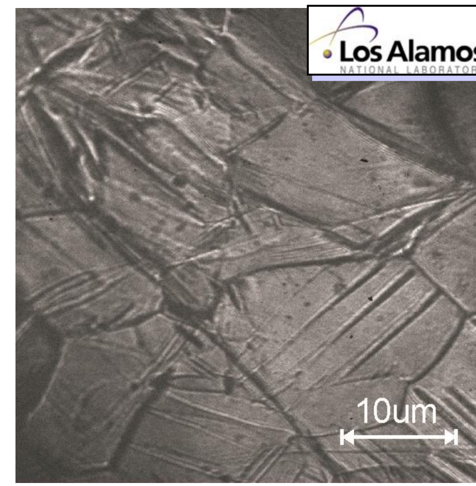
Single shot, 1.5 ns exposure

C. Brewer, et al, Opt. Lett. 33, 518 (2008)

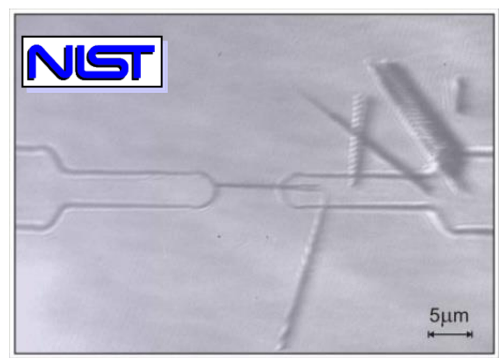
REFLECTION
NA=0.12 and 0.19 (M~250)
5-20 sec exposures



Partially Processed semiconductor chip



Zr surface showing twin in grain



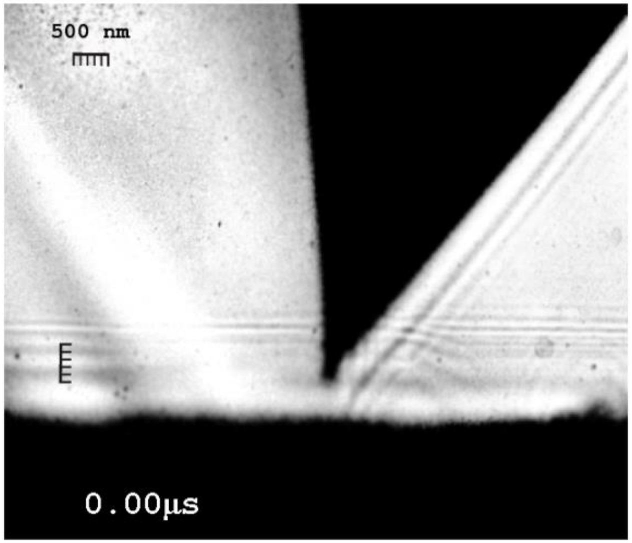
100 thick GaN nanowire between Al contacts

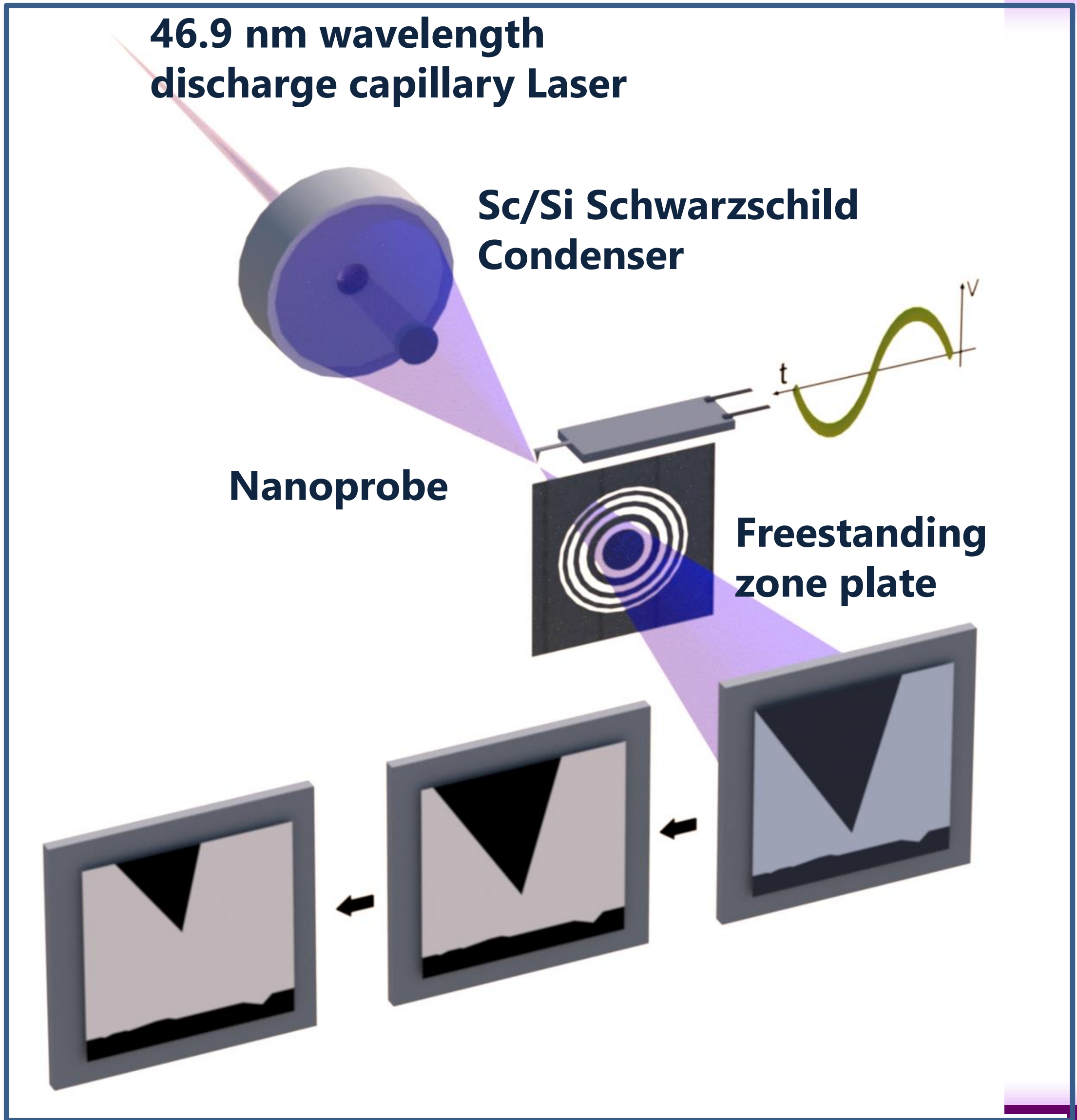
F. Brizuela et al, Opt. Express 13 :3983, (2005).

Single-shot sequential imaging
Motion picture of nanoscale dynamics

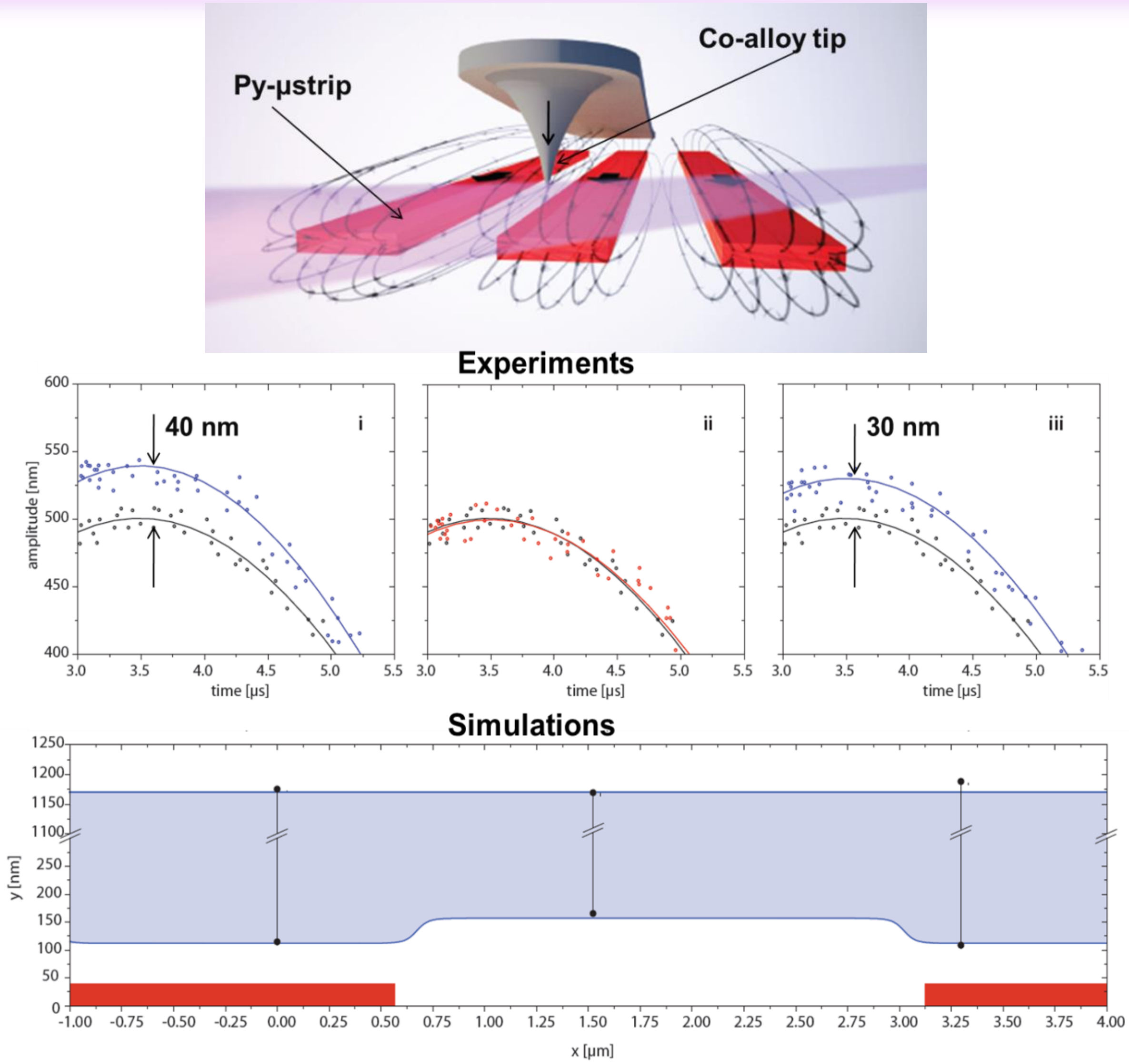
Laser Output at 46.9 nm
Energy > 10 μJ/pulse
($2.4\ 10^{12}$ ph/pulse)
Pulse duration ~1 ns

- Test object: Oscillating cantilever driven by periodic voltage signal
- Single shot images were acquired to map oscillation over an entire period





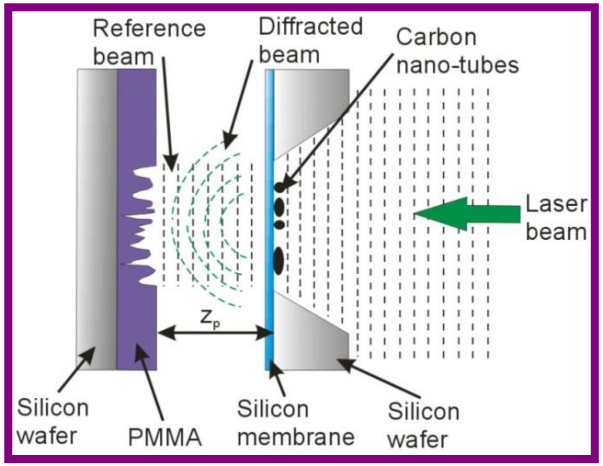
Visualizing magnetic nanoscale dynamics

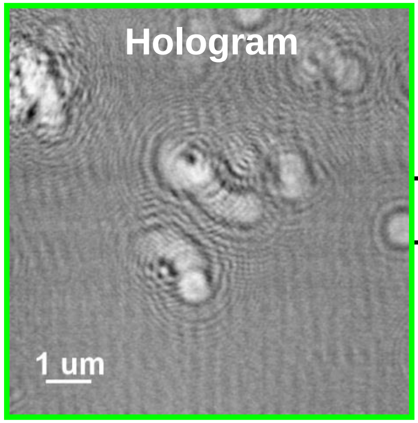


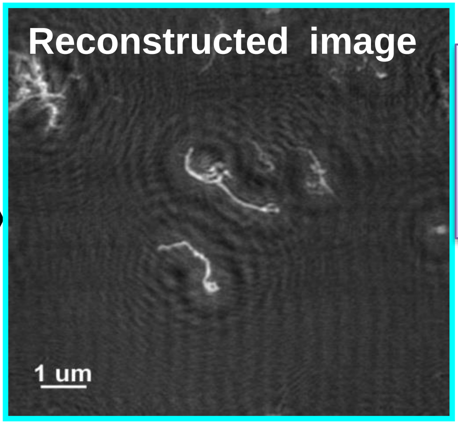
- **Variations of 30 nm in the amplitude of the oscillation detected.**
- **Model predicts change in the restoring force of the tip and associated amplitude changes that agree with experiment**

SXRL laser holography captures images with a single laser flash

IN LINE HOLOGRAPHY



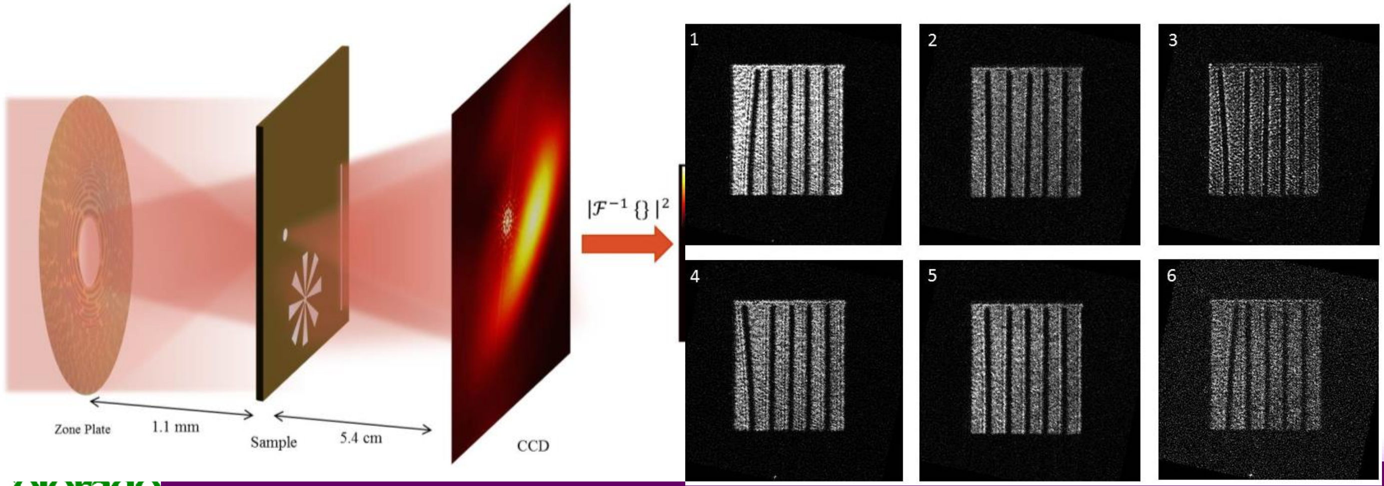




50 nm spatial resolution

P. Wachulak, JOSA B, 25, 1811(2008).

SINGLE SHOT EUV FOURIER HOLOGRAPHY CAPTURES MOTION OF NANOPILLARS



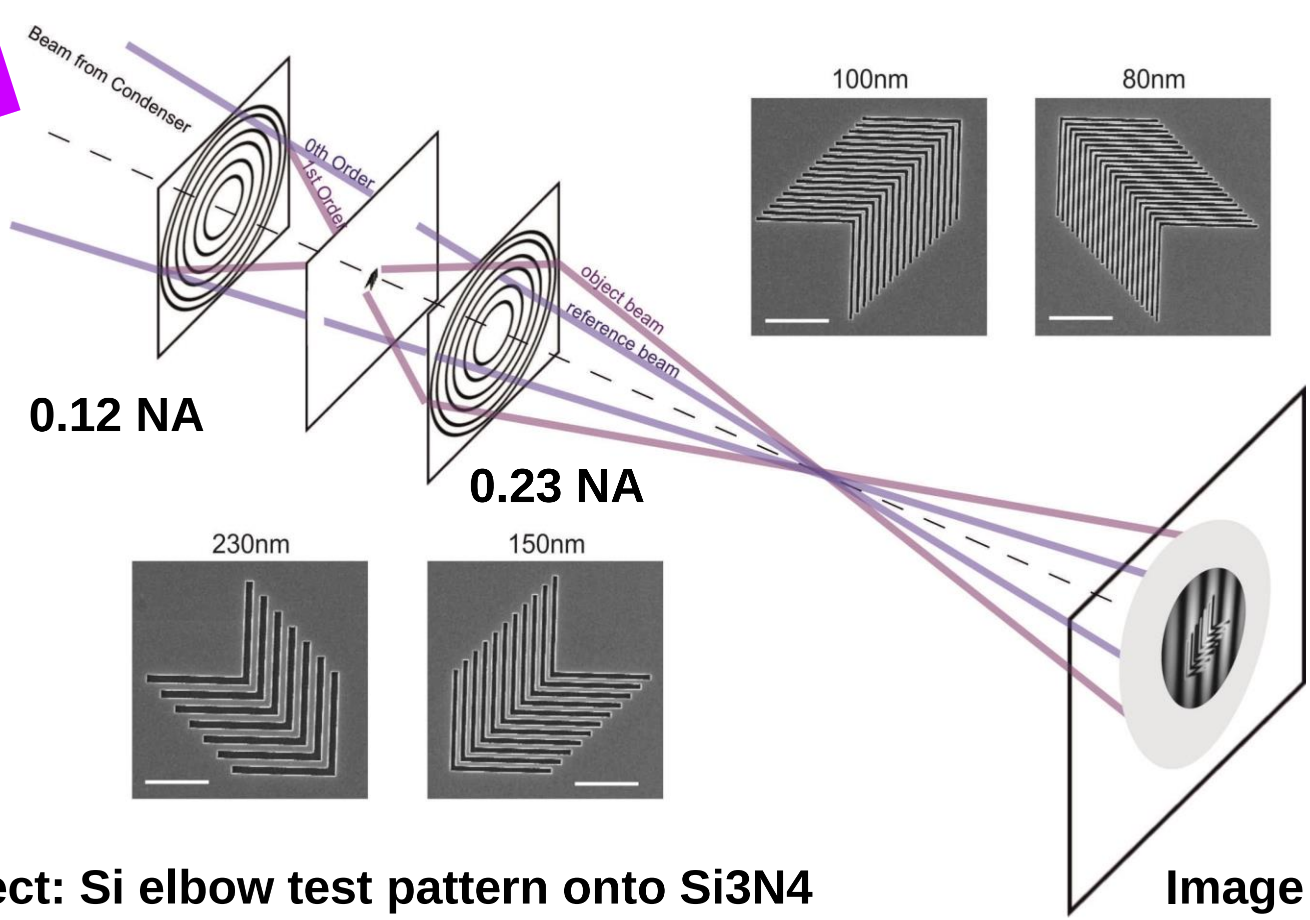
80 nm spatial resolution

E. Malm et al, Express:21:9959 (2013)

Marconi's group

EUV/SXR interference contrast imaging

λ=46.9 nm
SXRL
LC: 700 μm
TC: 90% of beam diameter
Pulse energy: 0.1 mJ



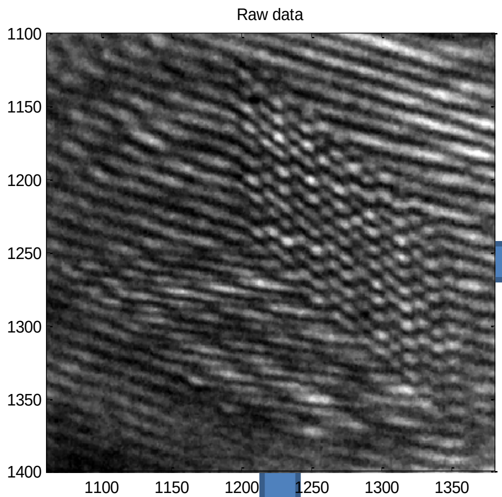
Object: Si elbow test pattern onto Si3N4 window– 30% absorption contrast @ λ=46.9 nm

Image plane hologram

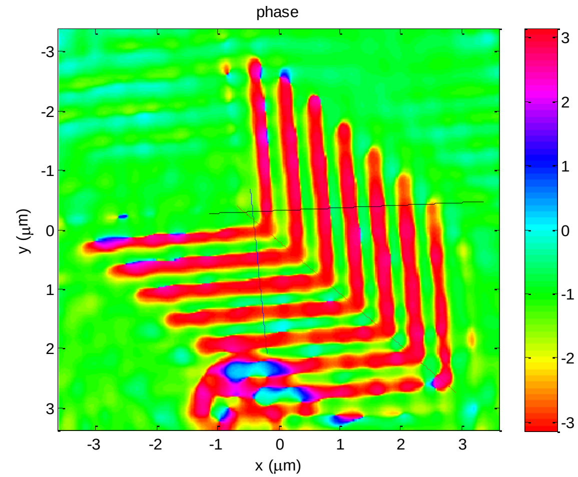
J. Nedjl et al, submitted to IEEE Photonics Journal

Full field images of a 230 nm dense line elbow pattern with 600x magnification

RAW IMAGE

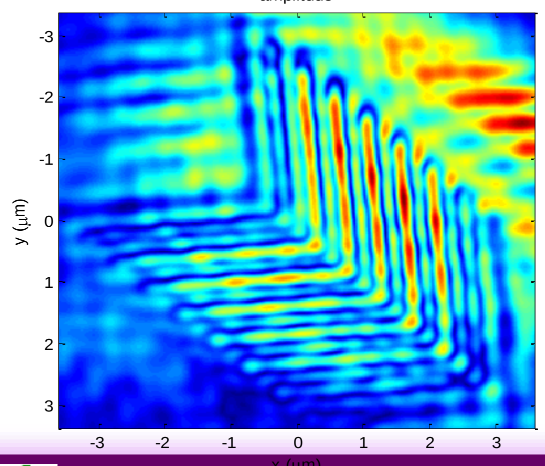


PHASE IMAGE

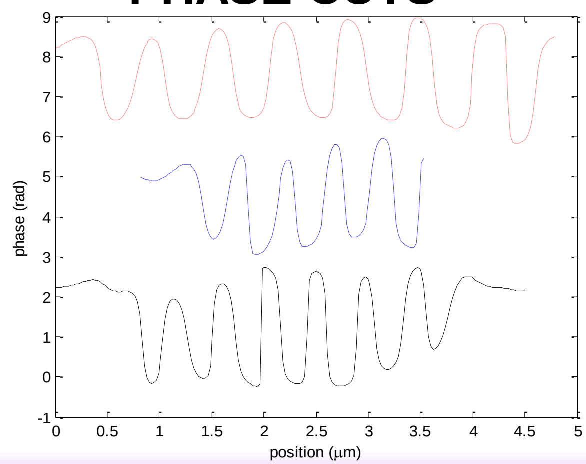


Phase difference of (2.3±0.3) rad corresponds to (100±15) nm thick Si

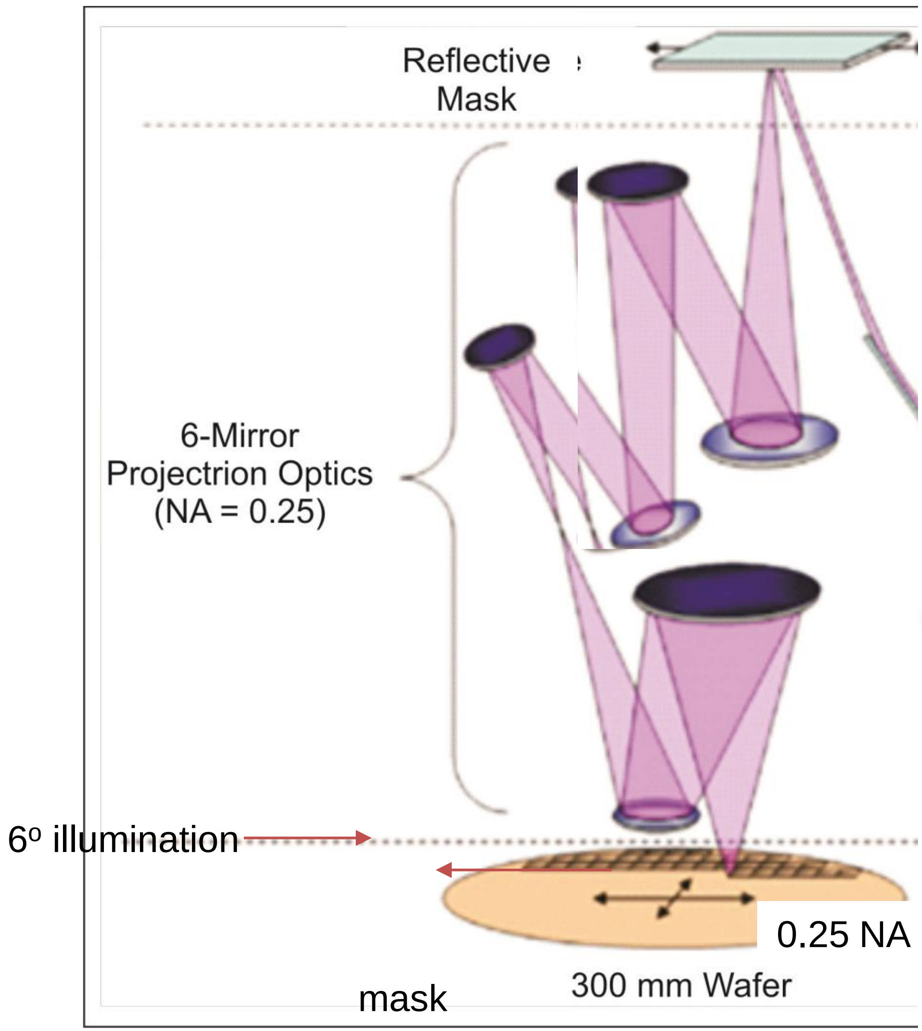
ABSORPTION IMAGE

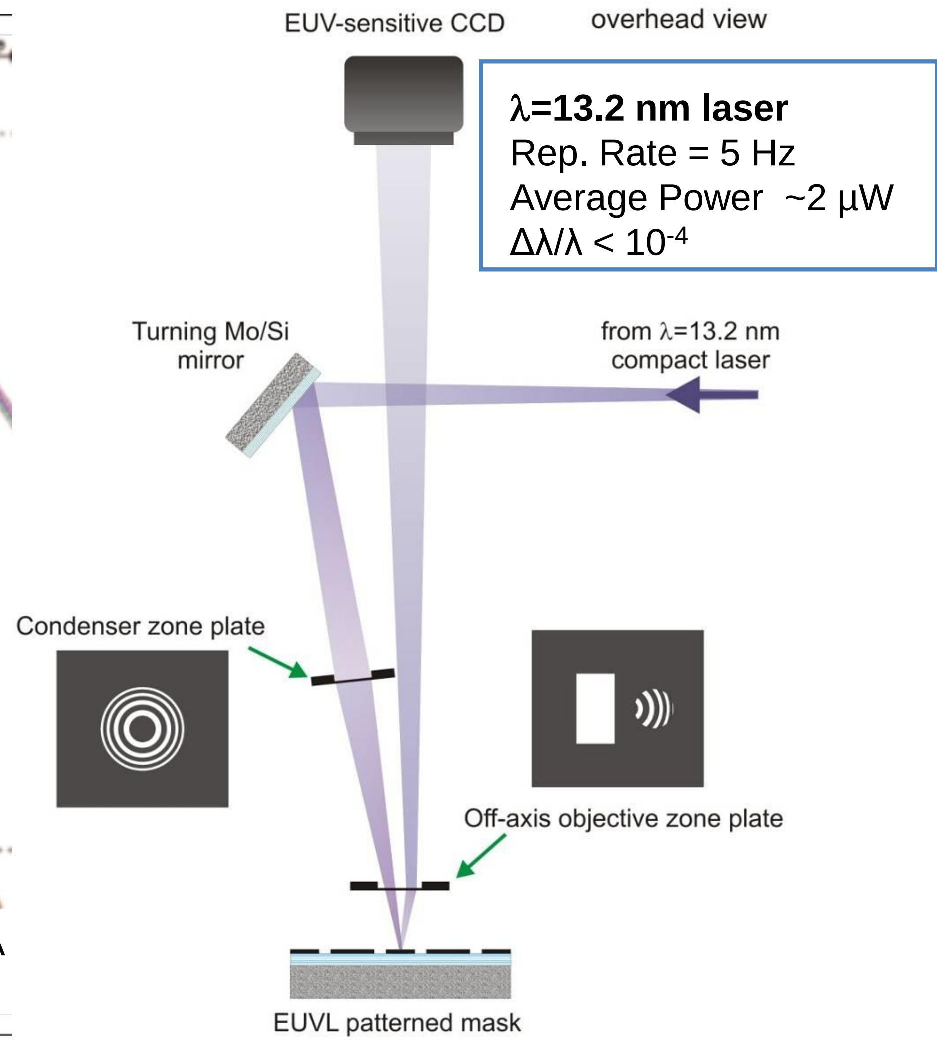


PHASE CUTS



λ=13.2 nm microscope for EUVL mask inspection illumination emulates EUVL stepper

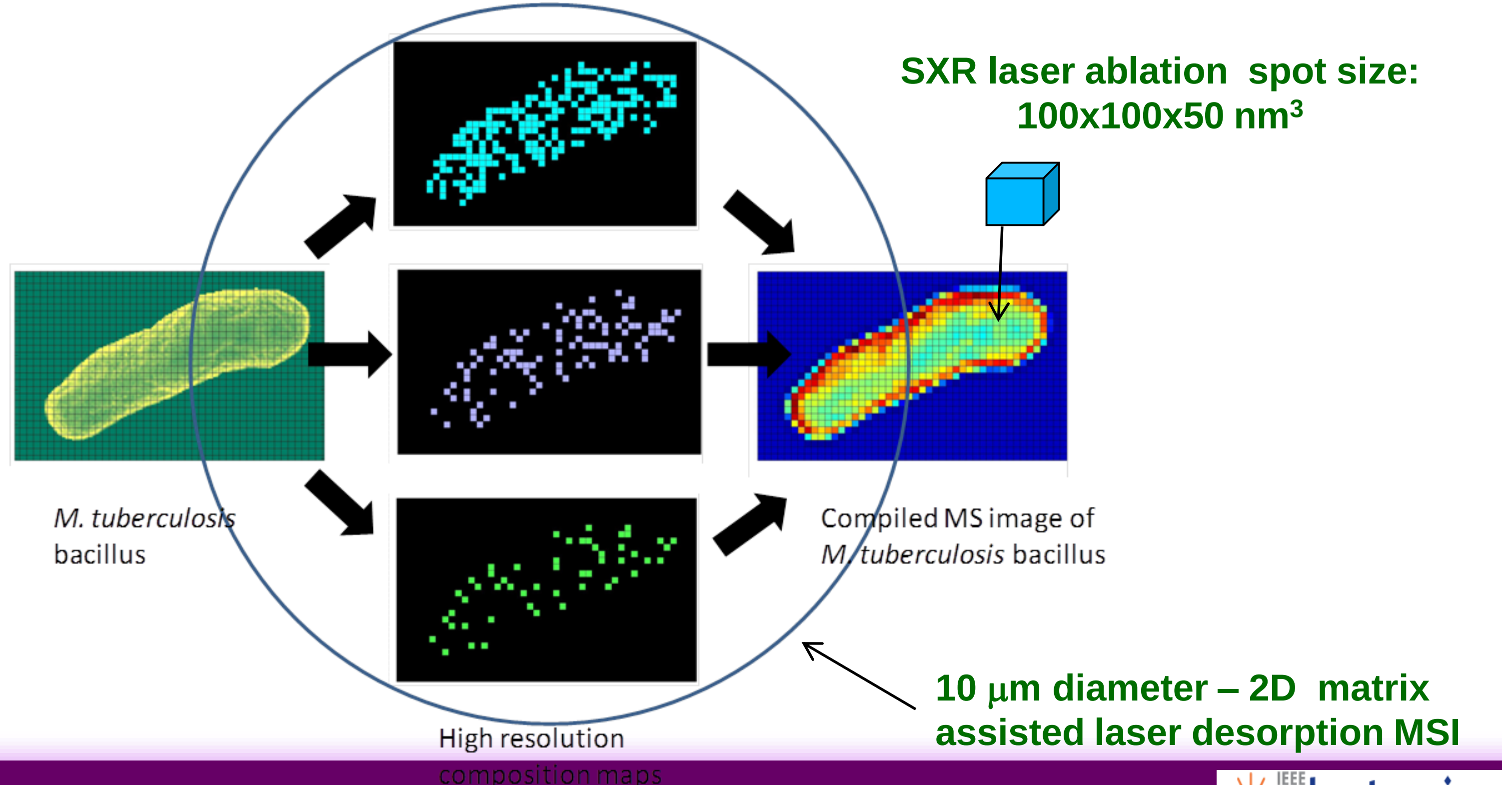




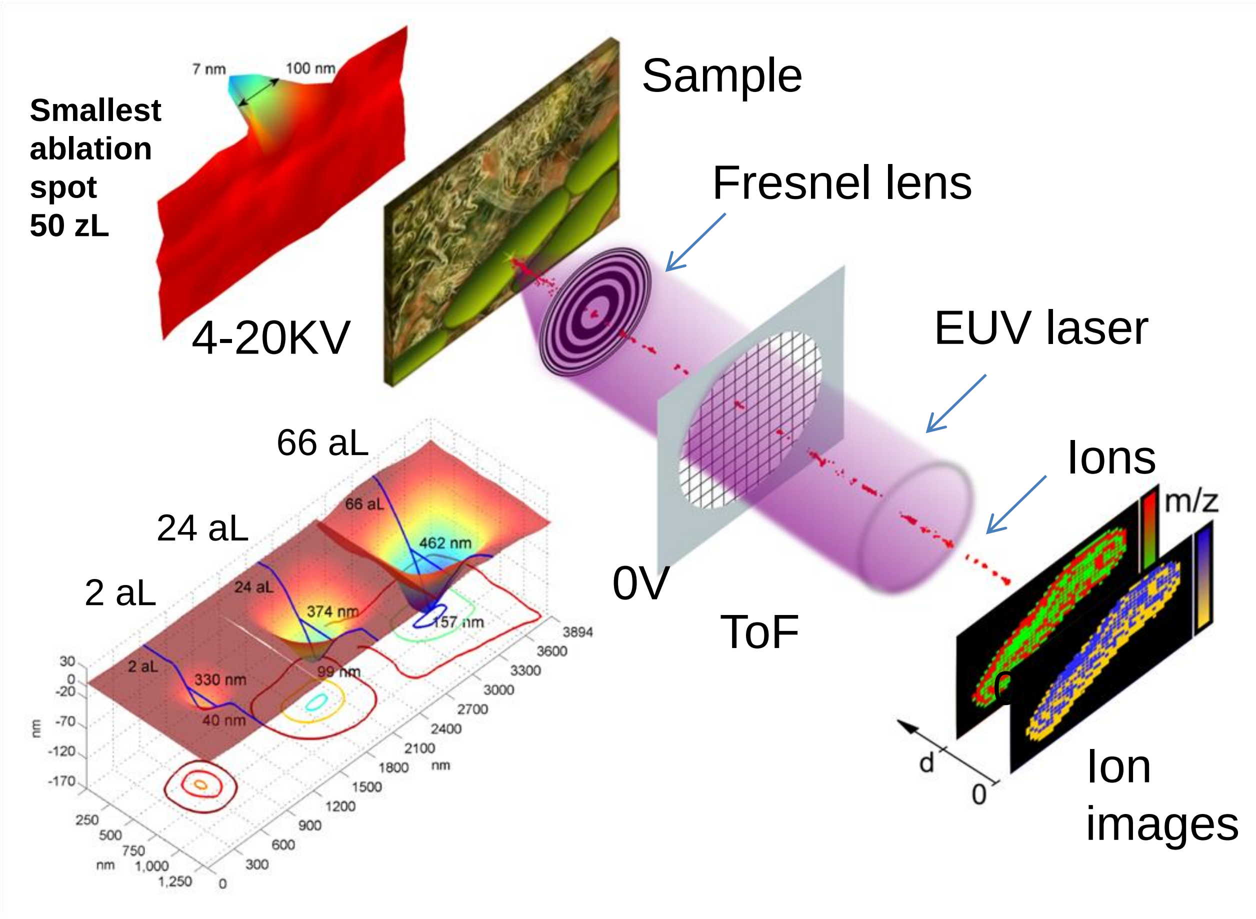
Nanoscale Molecular imaging by SXR laser ablation mass spectrometry

Mass Spectrometry Imaging (MSI) allows for identification of and mapping of the spatial distribution of elemental and molecular components in solid samples

CHALLENGES IN MSI of bio/organic samples to reach nanoscale resolution are:
- Reduction of ion yield when probing nanoscale volumes
- Molecular fragmentation



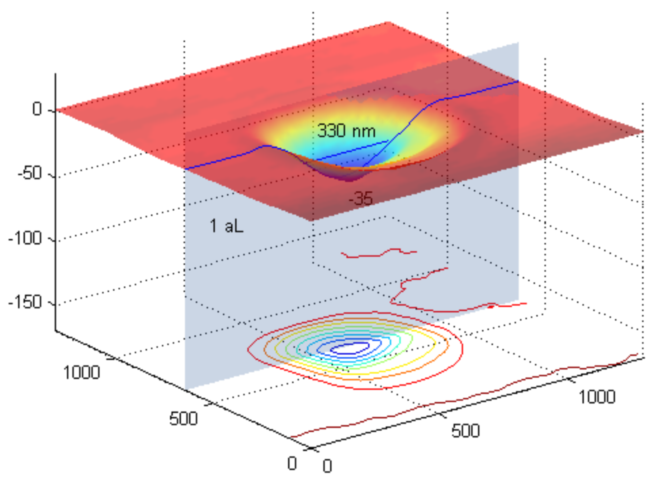
Concept of EUV/SXR Mass Spectrometry Imaging



- Laser pulses are focused onto specimen
  - •Wavelength: 46.9 nm
  - •Pulse duration: 1.5 ns
  - •Pulse energy: 0.01 mJ
- The focused laser ablates the material and simultaneously ionizes the fragments in the ablation plume
- Ions are extracted into the Time of Flight mass spectrometer

λ=46.9 nm laser ablation offers unique characteristics for MSI

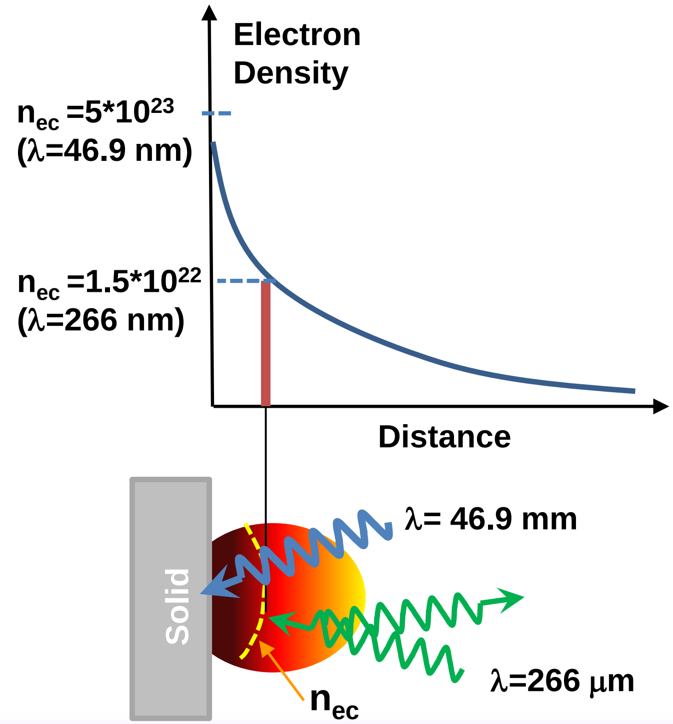
- **Exceptional lateral resolution:** λ = 46.9 nm light can be focused to ~100 nm spots [G. Vaschenko et al, Opt. Lett. Vol. 31, 3615-3617]
- **Exceptional depth resolution**: λ = 46.9 nm light is strongly absorbed in most materials
- **EUV photons break bonds in organic materials** [L. Juha et al, APL, Vol. 89, 034109 , 3009]



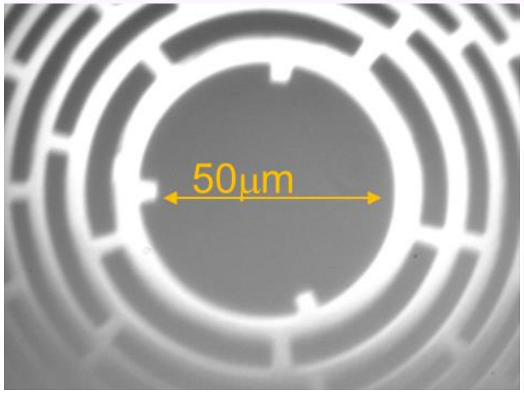
Profile of a crater with a volume of 1 aL ablated in PMMA with a single shot. The crater's profile shows no sign of thermal damage

EUV laser ablation and plasma generation

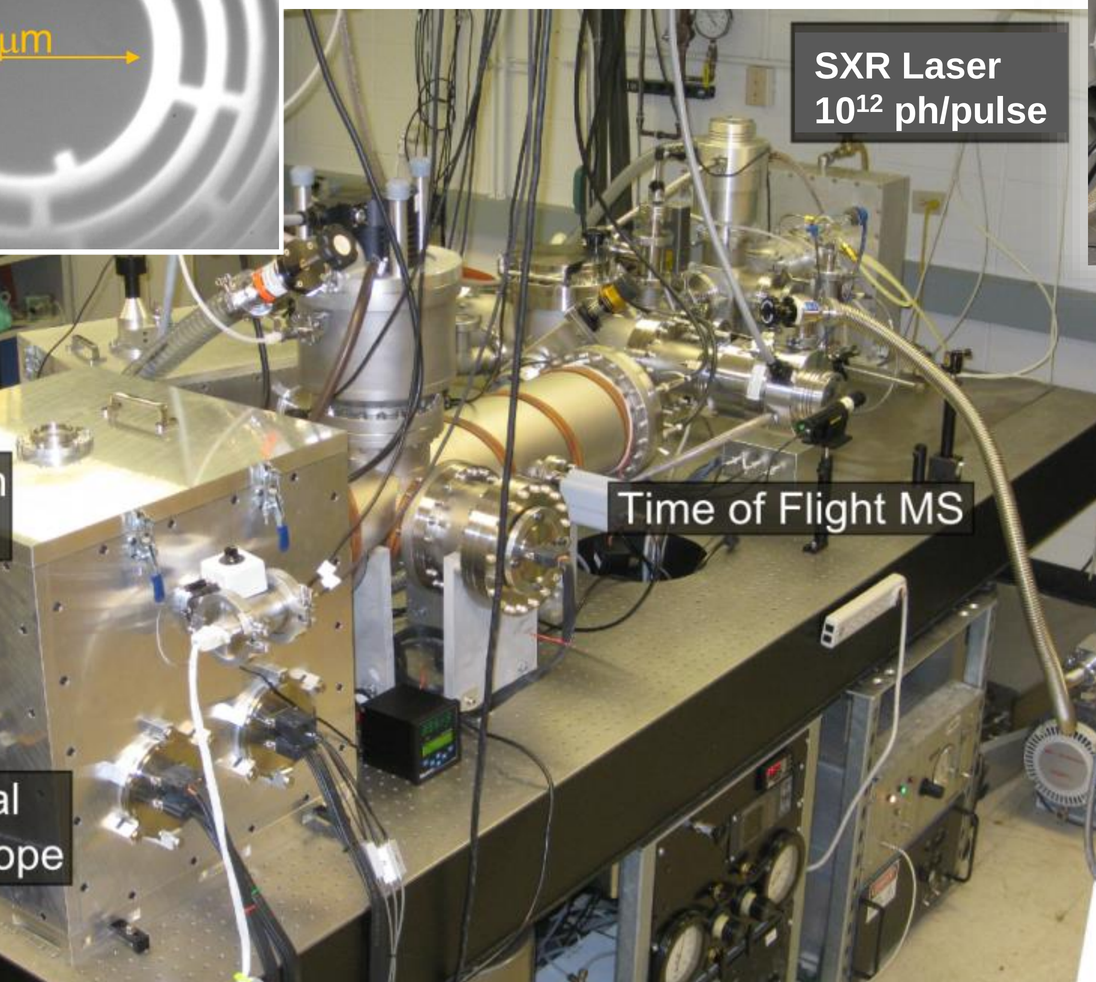
- Plasma is transparent to EUV photons
- Electron heating by inverse bremsstrahlung is negligible
- EUV photons absorbed by photoionization have sufficient energy to single photon-ionize any atom or molecule



3D imaging EUV mass spectrometry imaging nanoprobe



EUV Optics
Fresnel zone plate 0.16 NA



EUV laser

- **Wavelength: 46.9 nm**
- **Energy per pulse > 10 μJ**
- **Repetition rate: 12 Hz**
- **Pulse duration ~1.5 ns**

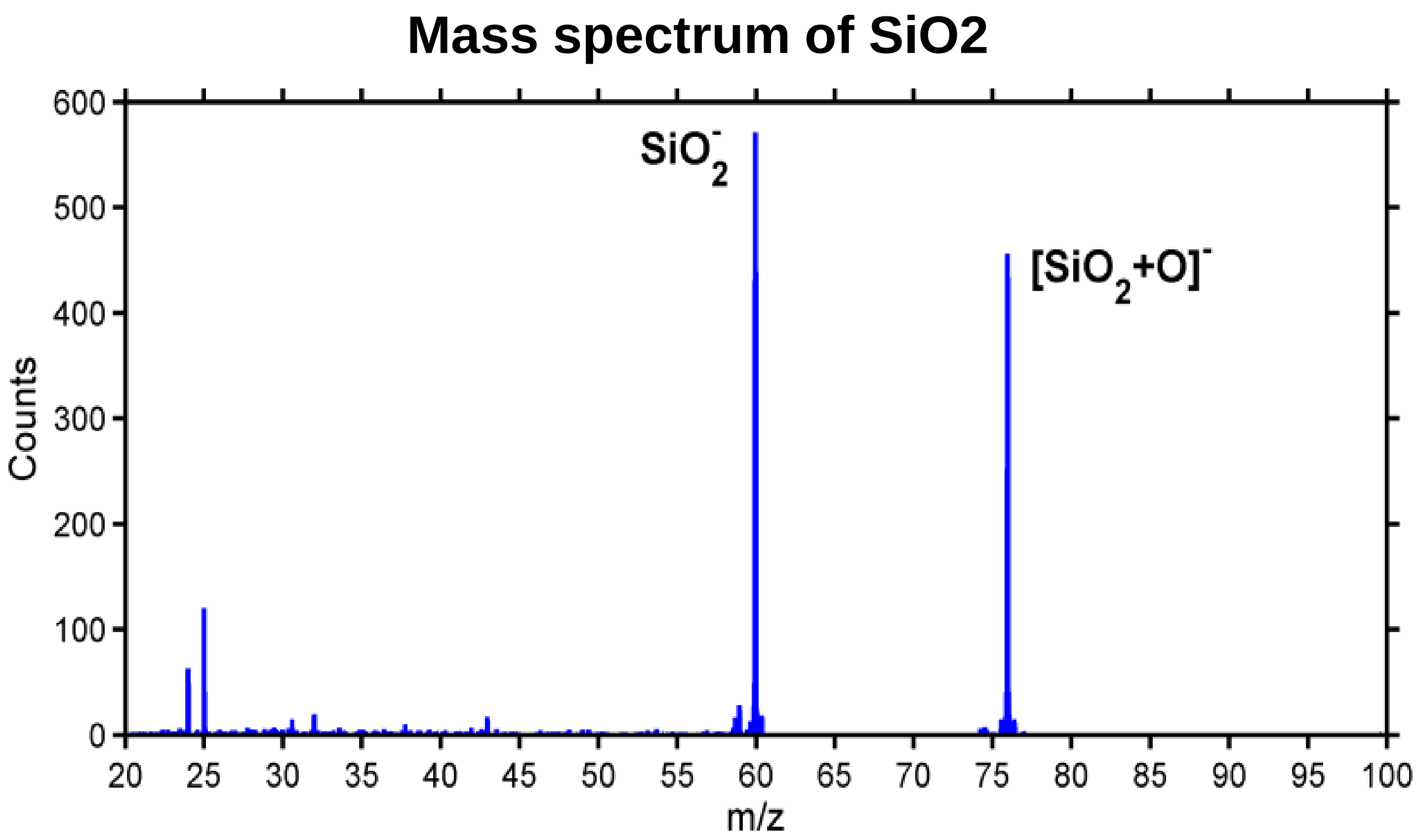
S. Heinbuch Optics Express vol. 13, 4050 (2005)

Optics engineered by W. Chao and E. Anderson at Center of X-Ray Optics, Lawrence Berkeley Lab.

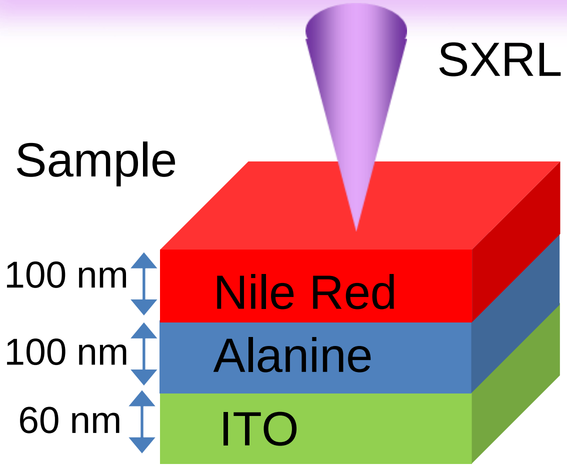
E.H. Anderson, IEEE J. Quantum Electronics, vol.42, 27, 2006

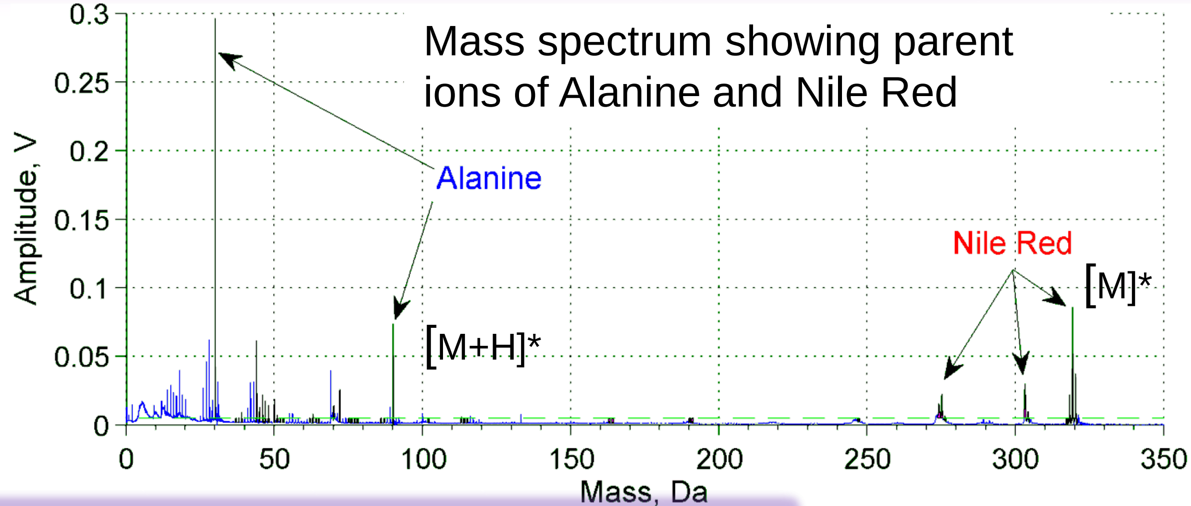
Results:

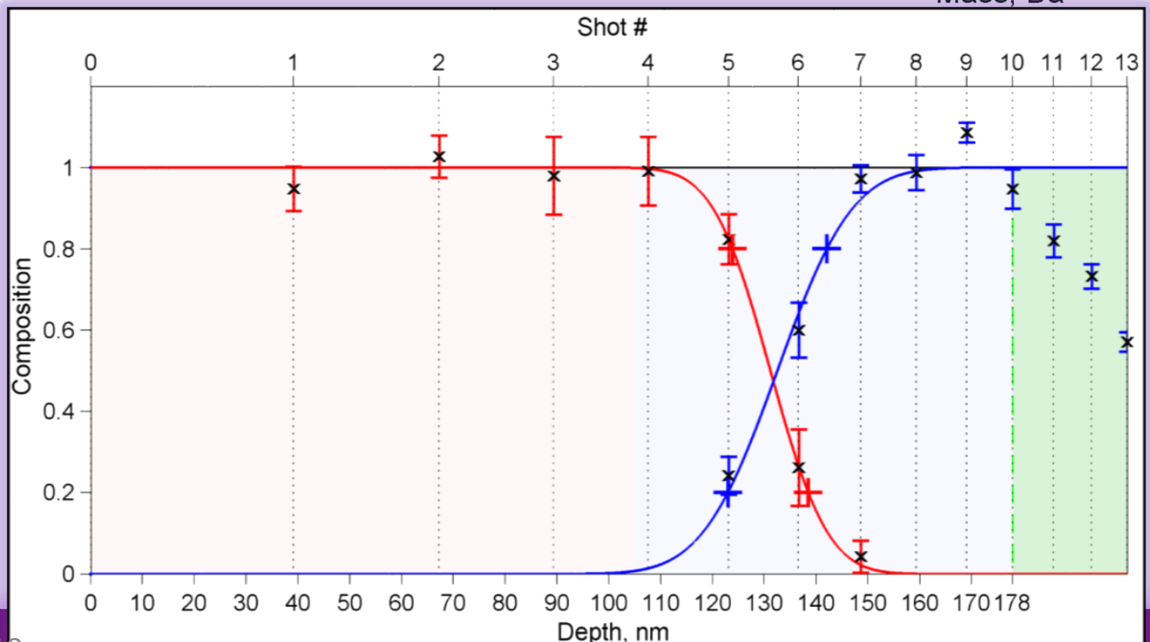
Molecular imaging of inorganic samples (negative mode extraction)



Results:
Depth profiling in organic samples with resolution ~ 20 nm

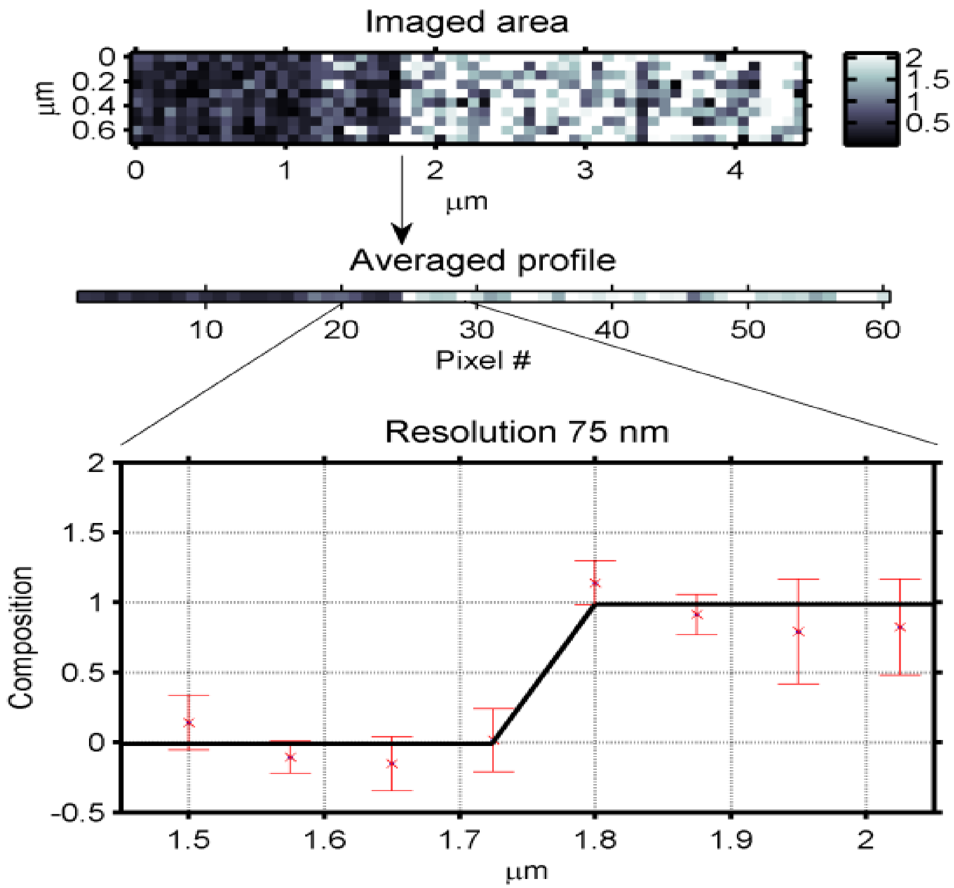




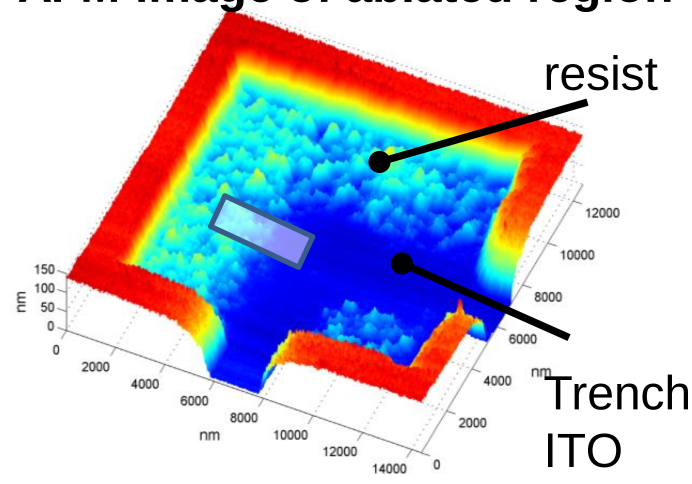


Results:
2D imaging with 70 nm lateral resolution

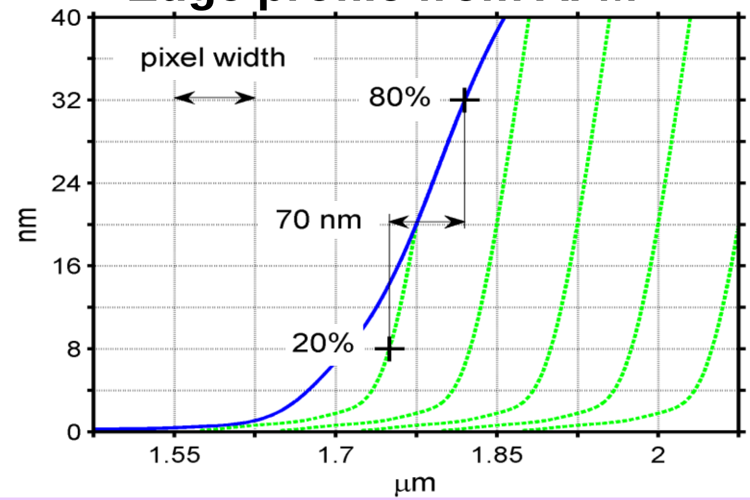
2D ion image plotting content of resist determined from the intensity average of 4 peaks in the 70-120 m/z range



AFM image of ablated region

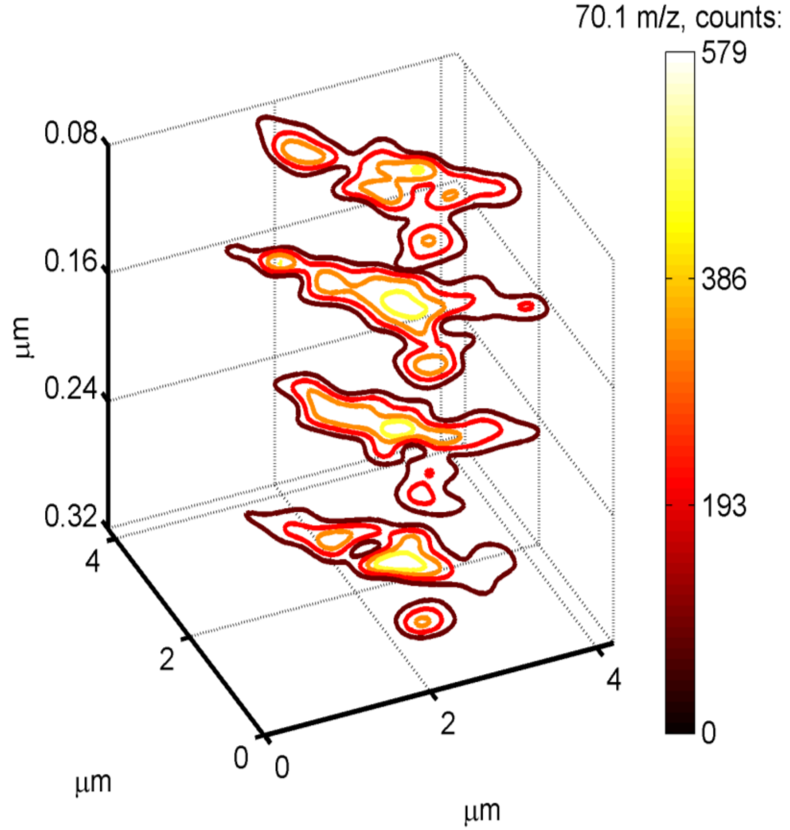


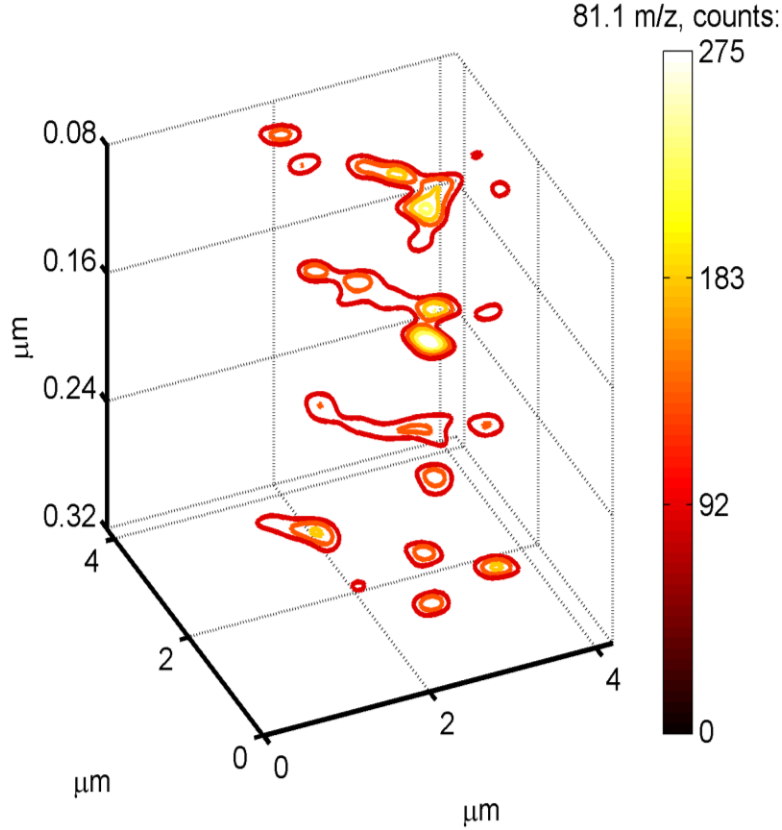
Edge profile from AFM



Results:
3D composition mapping of a single *M. Smegnatis* bacterium

Iso-lines of two significant lipid fragments



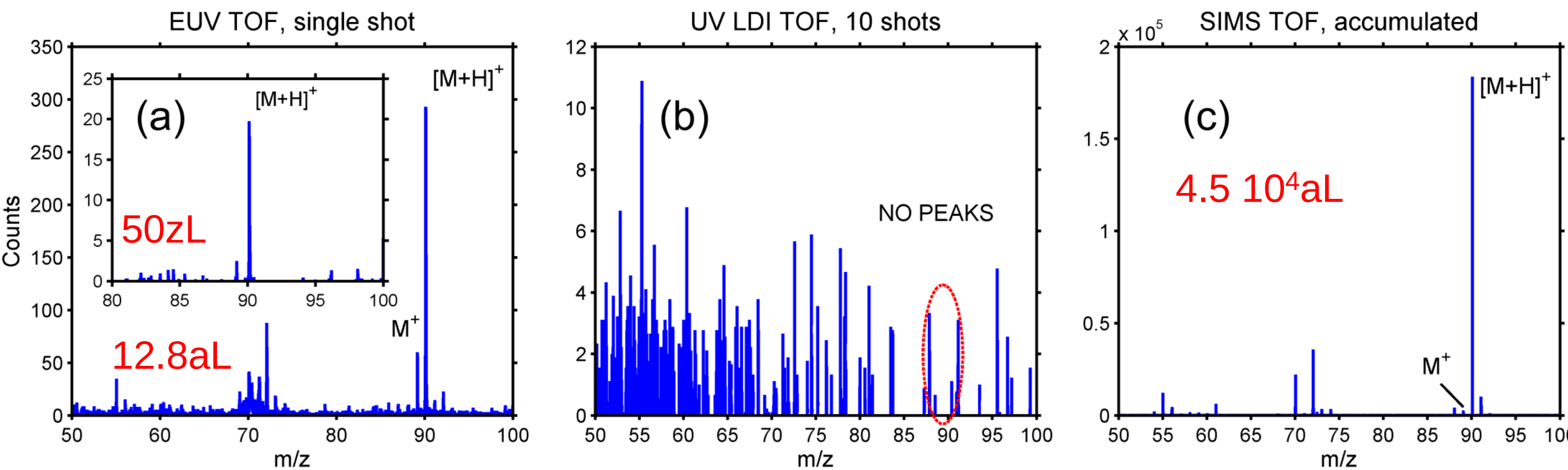


Voxel size: 0.3×0.3×0.08 µm^3

I. Kuznetsov, et al, to be published in Nat. Comm. 2015

Comparison of EUV TOF with leading molecular mass spectrometry methods UV LDI TOF and SIMS TOF

Mass spectra of alanine

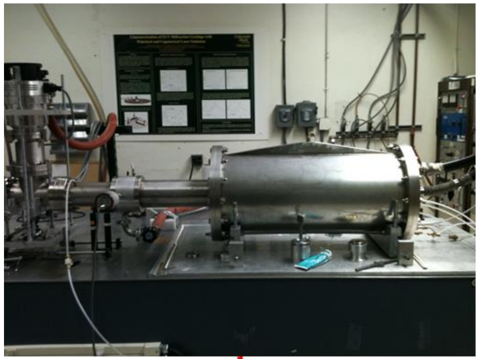


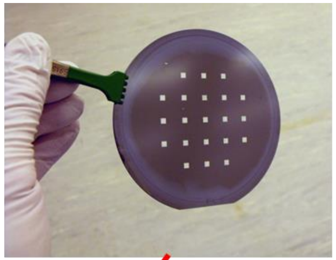
- Strong absorption
- High 3D localization
- Efficient photo-ionization
- **Sensitivity:0.01 amol**
- Fragmentation: 1.1

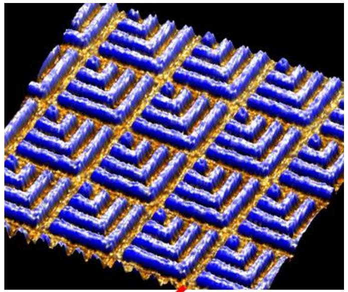
- Negligible absorption
- Absence of ionization
- (Requires Matrix)

- Ion collision process
- **Sensitivity:0.4 amol**
- Fragmentation: 1

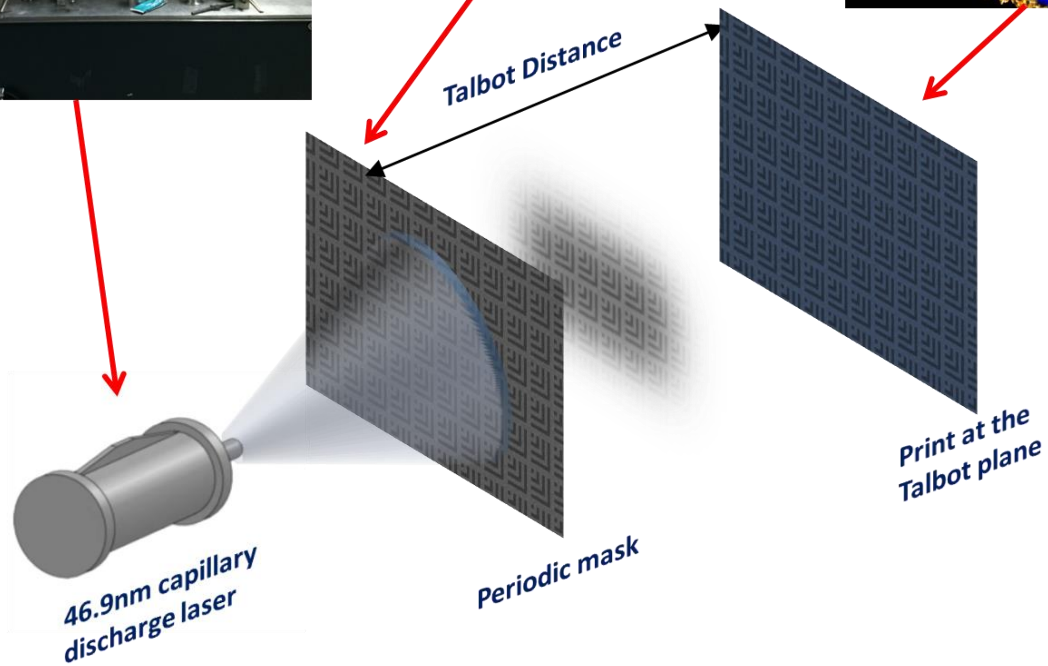
SXR Coherent lithography prints arbitrary motifs defect free







Talbot Distance

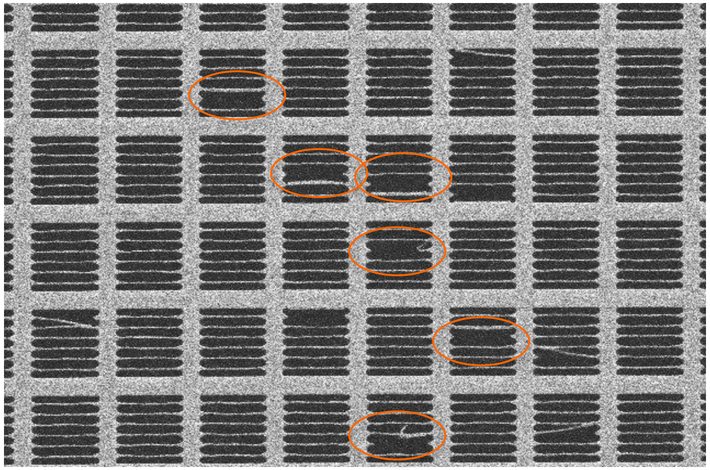


- NON- CONTACT
- LENSLESS LITHOGRAPHY
- SHORT EXPOSURES, 20-50 LASER SHOTS
- PRINTS PATTERNS DEFECT FREE OVER AREAS 0.5X0.5 mm^2

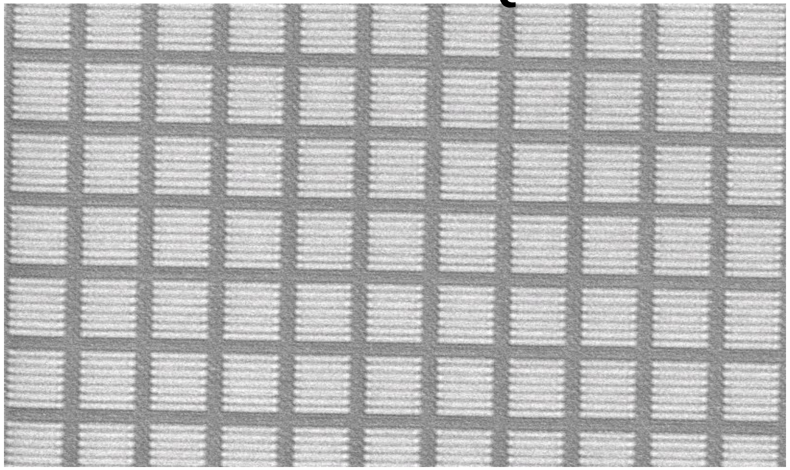
L. Urbanski, Opt. Lett. 37, 3633 (2012).

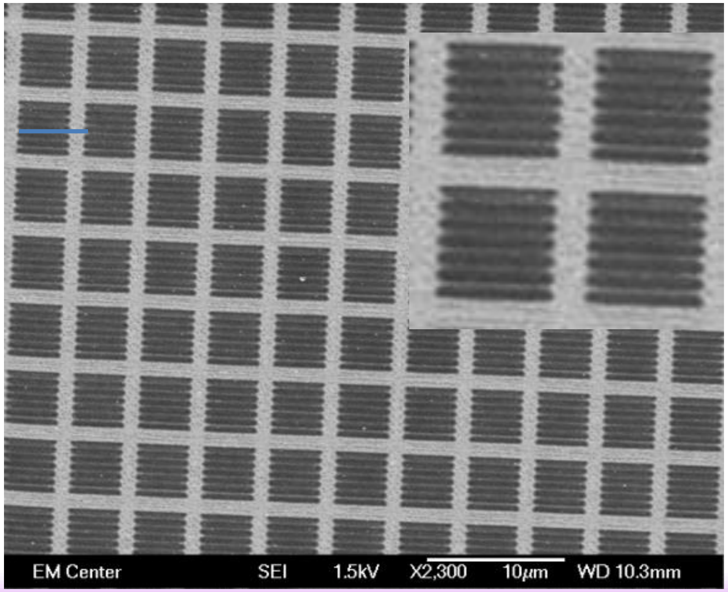
Error-Free Printing of Periodic metallic structures

Talbot Mask



Print in HSQ

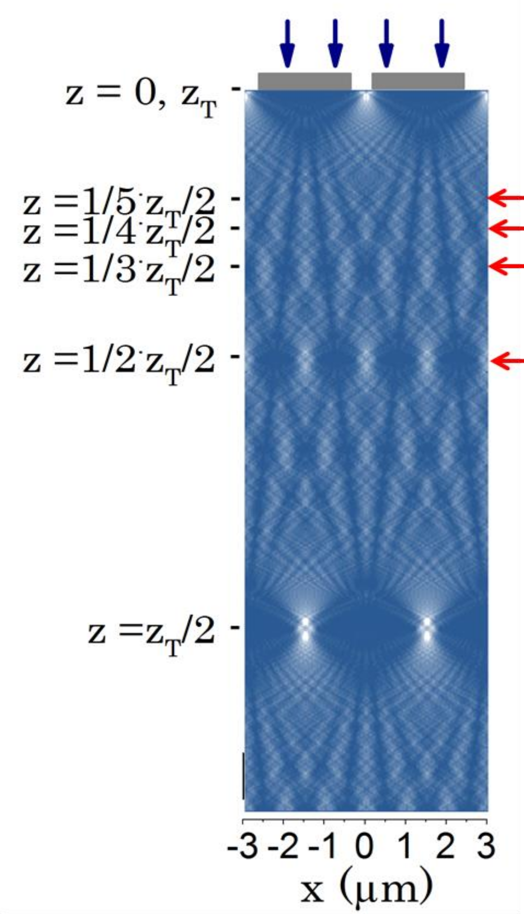




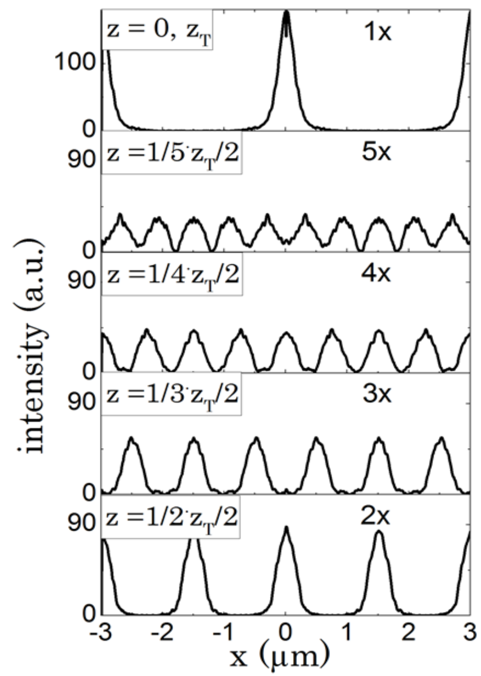
Grating etched in Au 500/600 lines/spaces

Smaller Features:
Fractional Talbot EUV Lithography

Periodic masks produce images with higher frequency in positions that are a fraction of the Talbot distance



Talbot carpet

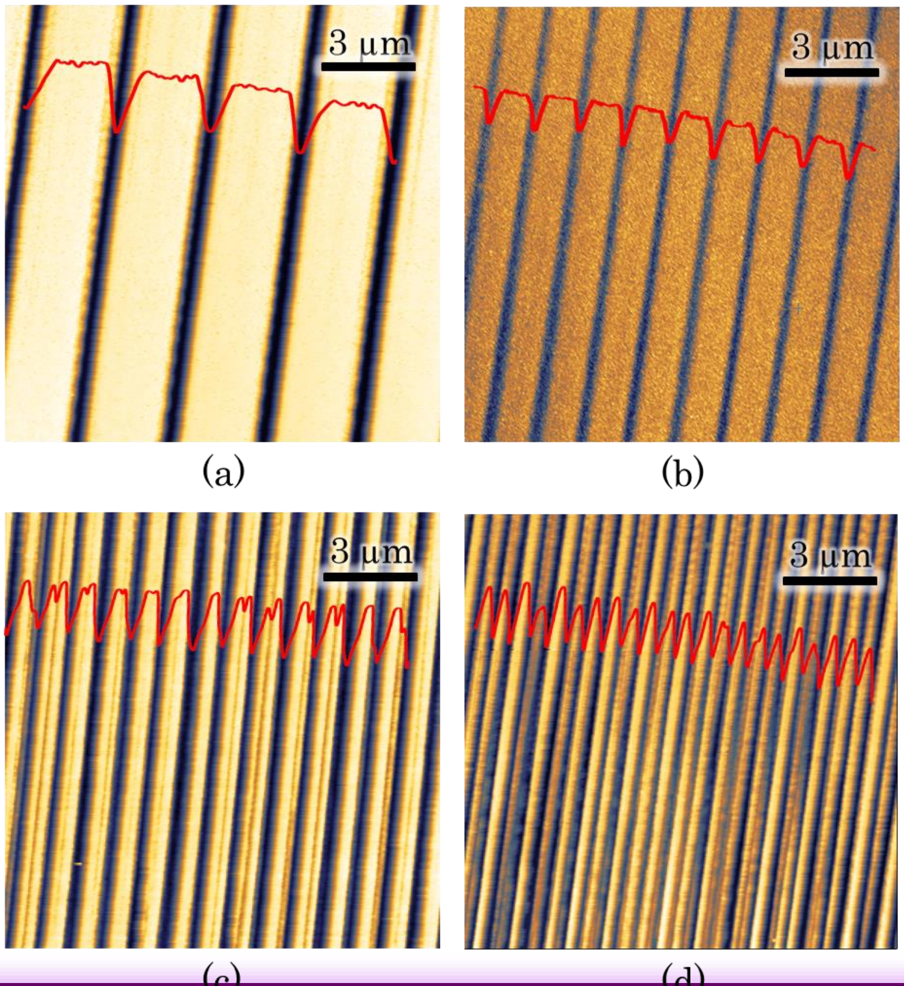


Intensity cross sections

Optics Letters, Doc. ID 224904

Frequency multiplication of periodic patterns by fractional Talbot lithography

Frequency multiplication factors up to 5X were demonstrated



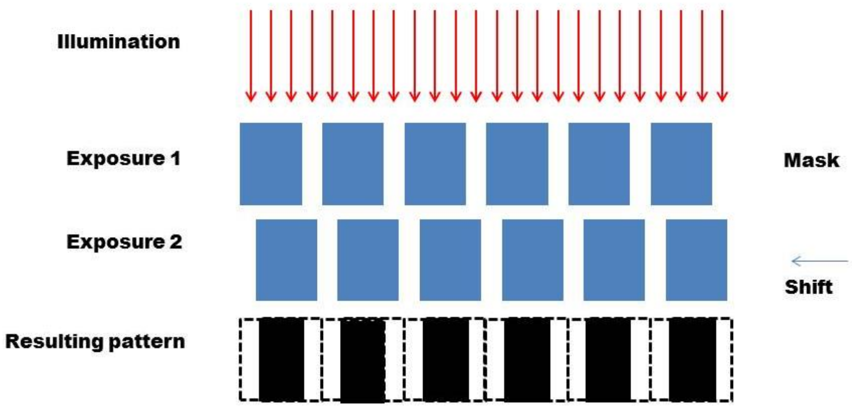
Fractional Talbot lithography with extreme ultraviolet light

Hyun-su Kim[1,4,*], Wei Li[3], Serhiy Danylyuk[2], William S. Brocklesby[4], Mario C. Marconi[3], and Larissa Juschkin[1]

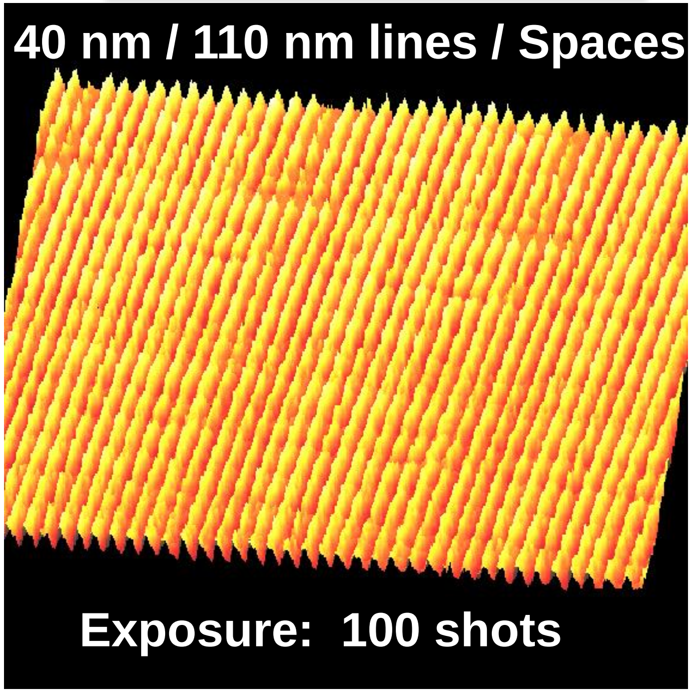
AFM measurements for the lithography results, showing (a) M_{sf} = 1, (b) M_{sf} = 2, (c) M_{sf} = 3, and (d) M_{sf} = 5 from the parent mask of 3 µm pitch.
Overlayed red curves show corresponding AFM cross-sections. The height of the PMMA structures (a-d) was ~ 80 nm.

Optics Letters, Doc. ID 224904

Double exposure and stitching prints 40 nm lines over millimeter square areas

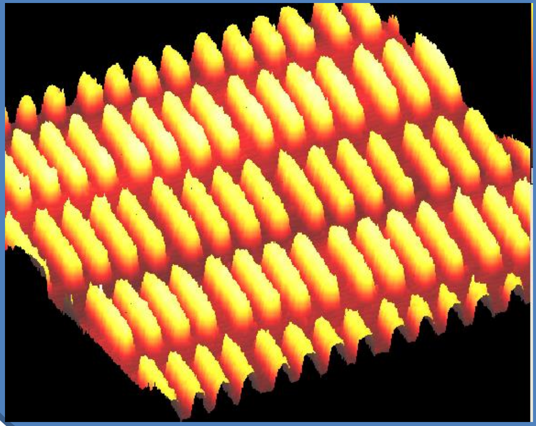


Smallest lines printed



Coherent Printing with 100 Hz, 18.9 nm laser

400 nm lines



1 Minute Exposure, 0.5 mm² Patterned Area

Potential to print 10 nm lines

Non contact printing method is well suited for studies of EUV resist response

L. Urbanski et al

Thanks to Collaborators

Microscopy Team

J. Nedjl, S. Carbajo, I. Howlett, N. Monserut, E. Malm, M.C. Marconi and K. Buchanan (CSU) (recent work)

Pioneers: G. Vaschenko, F. Brizuela

Mass spectrometry imaging team

I. Kuznetsov, J. Filevich, M. Woolston, T. Green, E. R. Bernstein, D.C. Crick, and J.J. Rocca (CSU)

NanopatterningTeam

W. Li, L. Urbanski, M.C. Marconi

Laser Engineering Team

Y. Wang, B. Reagan, M. Woolston, C. Baumgartner, A. Rockwood, S. Wang, L. Yin, J. Rocca (CSU)

Optics Engineering Teams

W. Chao, E. H. Anderson, K. Goldberg, P. Naulleau

Center for X-Ray Optics, Lawrence Berkeley Lab

A.   Vinogradov, I.Artioukov

Levedev Physical Institute, Russia

<u>AIR Research Alliance project </u>“
Development of Key Technology for next generation projection lithography of integrated circuits at <u>6.X nm wavelengths</u>”

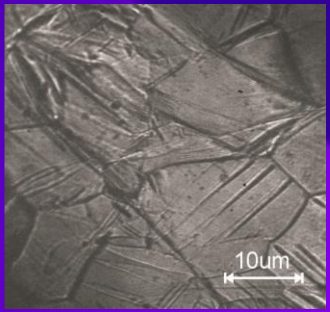
Collaboration between EUV ERC and Cymer

Funded by NSF and Cymer

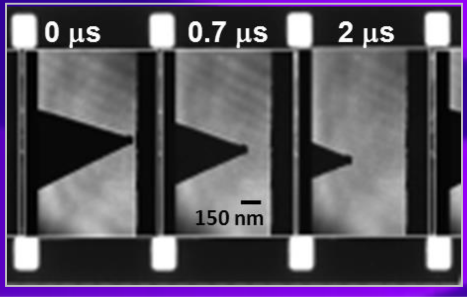
BRIGHT SXR LASERS ENABLE NOVEL TOOLS FOR NANOSCIENCE AND NANOTECHNOLOGY ON A TABLE TOP

TODAY

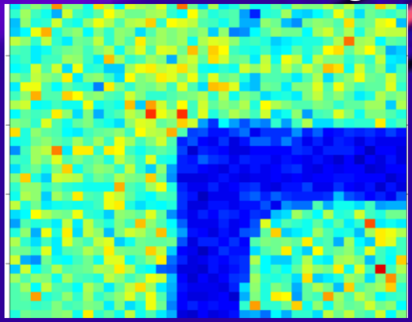
Imaging of nanostructures



Movies of nanoscale interactions

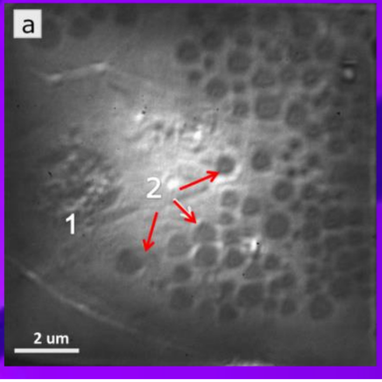


3D Molecular Imaging

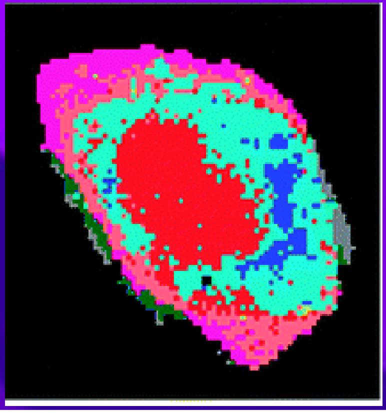


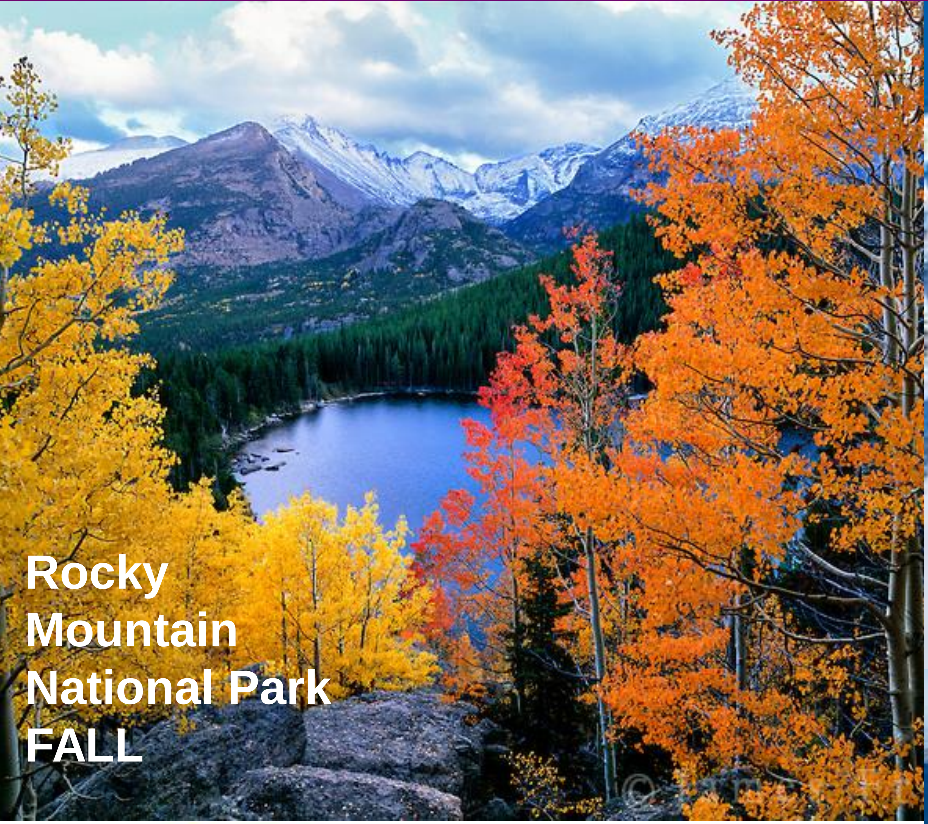
FUTURE

MICROSCOPY



3D MOLECULAR IMAGING





INTERNATIONAL
YEAR OF LIGHT
2015

Thank you!

Colorado State University

photonics SOCIETY